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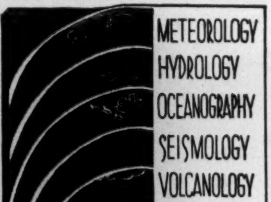
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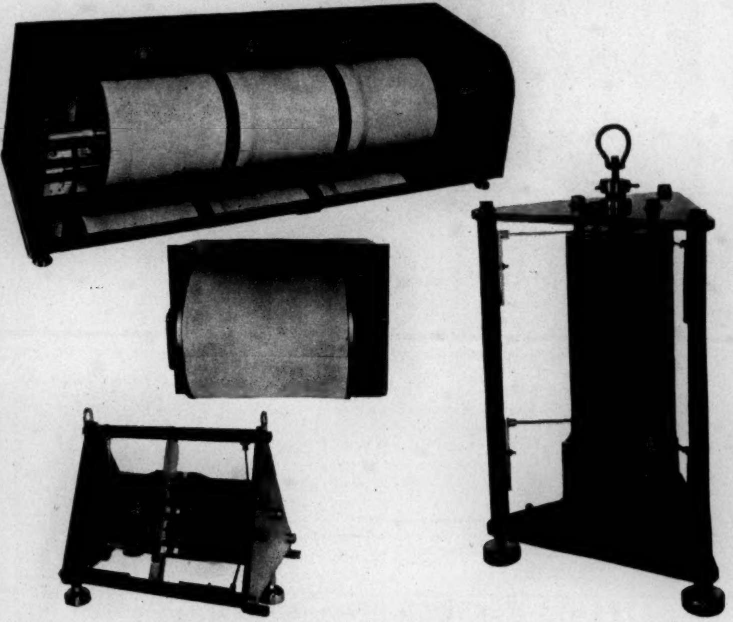

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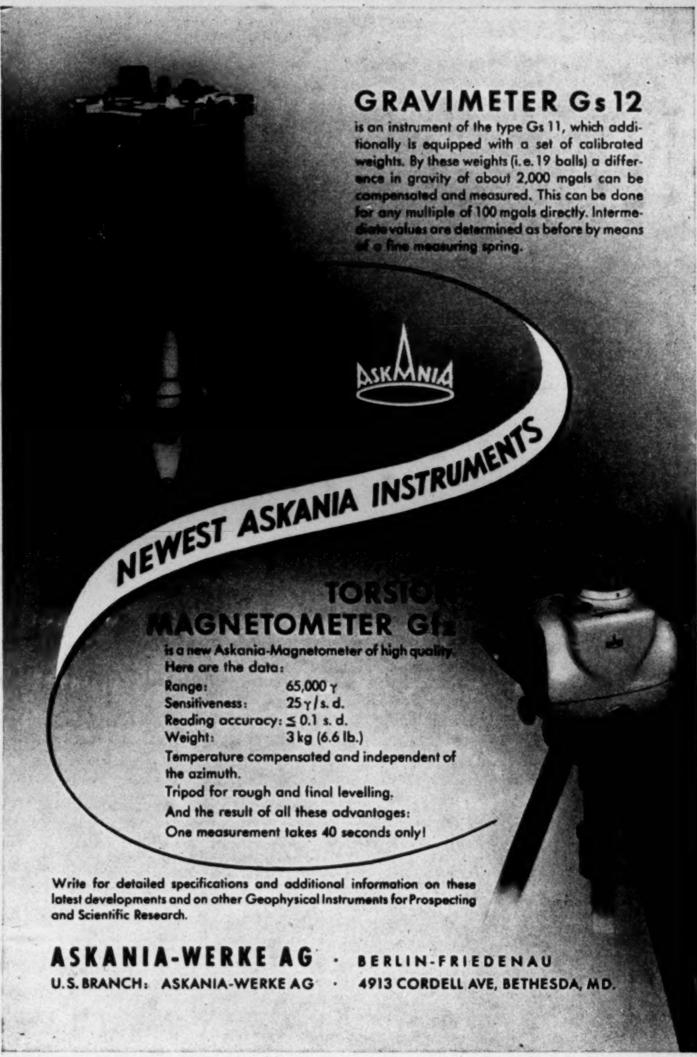

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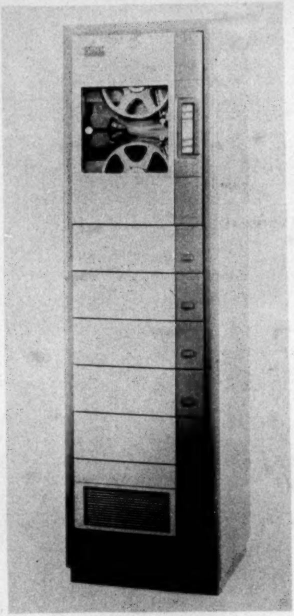

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Preface

This list of members, corrected for changes received by March 10, 1957, supplants the list of November 10, 1954, published as Part 2 of the Transactions of December 1954. Following the alphabetical lists of individual and corporation members is a geographical list, by cities and states or territories for the United States and possessions, by cities in Canada, and by countries otherwise. A third portion is a list of the Committees of AGU and its Sections, which in turn is followed by a list of publications of AGU.

In the main alphabetical and the geographical lists, the code letters following the names are the usual ones for the Section affiliations, as follows:

(a) Geodesy
(b) Seismology
(c) Meteorology
(d) Terrestrial Magnetism and Electricity
(e) Oceanography
(f) Volcanology, Geochemistry, and Petrology
(g) Hydrology
(h) Tectonophysics

Geophysics in its broad aspects is taking an increasingly important position with respect to science as a whole, and its importance to our national welfare and the welfare of the world as a whole is being increasingly recognized. The postwar General Assemblies of the International Union of Geodesy and Geophysics--the Eighth in Oslo in 1948, the Ninth in Brussels in 1951, and the Tenth in Rome in 1954--have shown the trend. The attendance at the General Assembly in 1954 was almost double that of 1948.

Recognition is also indicated by the development of the International Geophysical Year, 1957-1958, in which over 40 nations are participating, with activity in this concerted effort covering the most remote parts of the Earth, with concentrated effort in the Antarctic, and with observation points on isolated islands of the Pacific and in tropical regions. Few geophysical data are now available from many of these areas.

There are many well-qualified workers in geophysics who are not now members of AGU and who should be members in order that AGU may be of greatest usefulness. It is to the advantage and benefit of the present members if these are brought into membership. Please do what you can to bring in at least one new member. This directory, especially the geographical section, should be of help in determining whom to approach. We invite each member to consider himself a member of a Committee of Five Thousand to secure 5000 new members. Please do your utmost in this matter in order that AGU may be of maximum service to you, that it may grow and more nearly fulfill its aims with respect to the broad field of geophysics, science as a whole, and the welfare of Man. To facilitate this, an application form has been inserted at the end of this directory.

1515 Massachusetts Ave., N.W.,
Washington 5, D. C.,
March 1957

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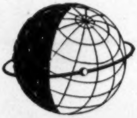

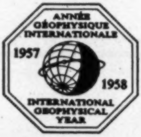
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University--W. B. Jones (d), D. B. Knowles (g), P. E. LaMoreaux (g), W. J. Powell (g)

Alaska

Anchorage--M. E. Nason (d), L. W. Tourville (c), R. M. Waller (g)
College--C. T. Elvey (cd), V. P. Hessler (d), C. J. Juedes (c), F. H. Leinbach, Jr. (d), W. B. Murcray (cdfh), L. Owren (d), T. L. Pewe (cg), M. Sugiura (d), W. S. Wilson (cd)
Fairbanks--M. C. Brewer (bd), T. C. Mathews (bcgh)
Juneau--R. I. Mayo (g)
Palmer--C. W. Wilson (g)
Sitka--J. L. Bottum (bd), K. A. Youmans (g)
Spenard--G. E. Fowler (abcfgh)

Arizona

Bisbee--J. F. Appleby (cg), J. A. Copeland (c), G. E. Daniels (cg), C. E. Erickson (cg)
Douglas--G. R. Fowles (d)
Flagstaff--C. G. Evensen (abcdefgh)
Fort Huachuca--M. O. F. Schroeder (ce)
Globe--E. Antevs (cg)
Grand Canyon--M. E. Kofford (fgh)
Jerome--R. W. Baldwin (bdeg), A. A. Brant (bcdgh)
Phoenix--L. R. Jurwitz (c), P. M. Lewis (ag), H. E. Skibitzke (ag), S. F. Turner (g)
Prescott--A. A. Still (abdfh)
San Manuel--E. J. McCullough, Jr. (bdh)
Scottsdale--W. L. Groene (c), H. J. Thiele (g)
Tempe--J. S. Horton (g), L. R. Rich (g)
Tucson--R. A. Bryson (c), M. E. Cooley (fg), G. E. Davis (g), R. B. DesJardins (c), L. W. Douglas (bc), J. E. Fletcher (g), L. Gwaltney (c), L. C. Halpenny (g), L. A. Heindl (fg), B. Hubbard (abdeh), P. W. Johnson (fg), A. R. Kassander, Jr. (bg), W. C. Lacy (bdfh), E. B. Mayo (fh), J. E. McDonald (c), A. M. Rugg, Jr. (dh), E. Schulman (cg), H. C. Schwalen (cg), G. E. P. Smith (g), R. F. White (bd)
Warren--W. D. Ohmstede (ce)

Arkansas

Benton--B. F. Armbrust, Jr. (f)
El Dorado--L. E. Garrison (e), C. J. Hoke (abg)
Fayetteville--K. Engler (g), P. K. Kuroda (efg)
Fort Smith--J. L. Saunders (g)
Harrisburg--C. V. Freeman (bdfgh)
Hot Springs--D. S. Libbey (cg)
Little Rock Air Force Base--J. G. Gamble (ce), H. C. Getty (cg), E. B. Madden (g), J. H. McHughs (cg), E. C. Meserve (cg), I. E. Miller (g), J. W. Moses (cg), M. S. Petersen (g), J. C. Pyle (g), J. E. Reed (befgh), R. T. Sniegocki (abdgh)
North Little Rock--O. B. Yaeger (g)
Stuttgart--R. G. Kazmann (g)

California

Albany--F. H. Moffitt (aeg)
Alhambra--G. F. Francis (b), H. C. Troxell (gh)
Altadena--S. E. Blewett (c), E. Bollay (ceg), T. H. Braun (b), K. E. Hunter (bdh), R. A. Peterson (g)
Anaheim--W. L. Burnham (g)
Aptos--C. S. Jarvis (egh)
Arcadia--A. L. Himelhoch (g)
Arlington--P. D. Williams (d)
Avenal--W. D. M. Reeves (g)
Bakersfield--W. T. Balch (cg), J. S. Bigelow (h), E. S. Bliss (g), J. G. Cole (bdegh), C. E. Johnson (g), J. C. Manning (g), L. Schiff (g), C. H. Williams (g), J. Zimmerman, Jr. (bf)
Belmont--H. E. Root (cg)
Berkeley--F. Adams (g), J. E. Alverson (cg), H. W. Anderson (cg), F. B. Blanchard (g), G. B. Bodman (g), L. N. Brown (g), P. Byerly (bh), A. S. Campbell (e), C. W. Chesterman (fh), N. Chien (eg), F. B. Clendenen (g), A. Court (cg), P. R. Day (g), H. A. Einstein (g), W. L. Fons (cg), C. M. Gilbert (efg), S. T. Harding (g), N. E. A. Hinds (befg), J. W. Johnson (eg), G. Kalkanis (ceg), P. F. Keim (g), S. R. Keim (egh), J. E. Kesseli (cefg), J. B. Leighly (cg), L. B. Loeb (cd), M. Markowitz (ceg), W. W. McLaughlin (g), C. Meyer (abdf), K. B. Morrissey (cg), E. L. Neff (g), R. D. Ogg (e), J. B. Orr (f), T. H. Pagenhart (g), E. R. Rowe (cg), F. C. Scobey (g), R. E. Storie (g), D. Tocher (abefh), D. K. Todd (ceg), P. D. Trask (ceg), F. T. Turcotte (befh), F. J. Turner (h), J. Verhoogen (bdfh), R. L. Wiegel (e), H. Williams (efh), E. H. Wisser (fh)
Beverly Hills--C. Aston (abd), T. V. Crawford (cg)
Big Sur--G. G. Healey (d)
Bishop--T. J. Henderson (cg)
Burlingame--E. W. Adams (abcdefgh), K. Kaplan (e)
Campbell--A. E. Jones (bfg), J. H. Snyder (g)
Camp Irwin--K. E. Beebe (eg)
Carmel--C. P. Vetter (acg)
Carmichael--F. C. Craig (g), W. W. Peak (g)
China Lake--C. L. D'Ooge (c), P. St. Amand (abdh)
Citrus Heights--J. D. Goodridge (cg)
Claremont--J. F. McAllister (f), W. J. Miller (befh), J. S. Shelton (bcfgh), W. C. Smith (fgh)
Cloverdale--G. Dewart (f)
Coleta--E. F. Serr, III (cg)
Concord--C. A. Morelli, II (abcfgh)
Covina--E. A. Withers (g)
Culver City--W. F. Garber (ceg)
Daly City--W. A. Waldorf (bcg)
Danville--R. W. Goranson (bfh)
Davis--L. J. Booher (g), F. A. Brooks (c), R. H. Burgy (g), L. D. Doneen (g), R. M. Hagan (g), A. H. Hendrickson (g), C. F. Kelly (cg), J. N. Luthin (cg), J. C. Marr (g), V. H. Scott (g), E. F. Serr, II (g), F. J. Veihmeyer (cg)
El Cajon--J. Kahl (ce)
El Centro--J. D. Hess (g)
El Cerrito--C. A. Davidson (ag), E. D. Kane (c)
Encinitas--M. C. Chittenden (b), J. D. Isaacs (ed)
Encino--F. D. Voris (cd)
Eureka--I. E. Anderson (cg), V. J. Hansen (cg), J. J. O'Brien, Jr. (g)
Fresno--A. R. Addington (bg), L. Costedoat (g), C. Hobe (abg), H. Karrer (g), E. F. Sullivan (g), C. L. Walton (g)
Fullerton--K. E. Brunot (e), J. W. Higgins (afgh), J. W. Spencer (bdegh), R. E. Stevenson (e)
Gardena--B. T. Pleimann (bf)
Glendale--M. Bookman (g), S. F. Bush (cg), J. E. Jones

(g), F. E. Schoonover (bg), E. R. Stauffacher (cg), F. E. Tatum (g)
Glendora--C. C. Green (g), E. L. Hamilton (cg), R. A. Merriam (g), P. B. Rowe (cg), J. D. Sinclair (cg)
Goleta--J. B. Powers (c)
Granada Hills--F. S. Johnson (cd)
Hawthorne--E. C. Hartman (cdg)
Hollywood--O. H. Truman (ab)
Huntington Park--M. N. E. Rifai (g)
Imperial Beach--H. C. Myers (g), G. F. Warn (abcdefgh)
Independence--G. A. Lewis (g)
Inglewood--W. O. Byrd (a), W. Silva (b), J. R. Stipp (g), E. J. Zielbauer (g)
Kentfield--J. S. Cotton (cgh)
La Canada--W. J. Carroll, Jr. (cg), J. W. Dunham (e), R. L. Nevin (g)
Lafayette--J. E. Taylor (g)
La Habra--E. C. Nixon (h), N. A. Riley (cgh), G. C. Werth (bde)
La Jolla--R. S. Arthur (ce), M. N. Bramlette (aeg), E. E. Collias (e), C. S. Cox (e), T. Cromwell (e), C. Eckart (de), W. M. Elsasser (cd), T. R. Folsom (e), J. D. Frautschy (aeg), E. D. Goldberg (ae), G. W. Groves (e), D. L. Inman (eg), L. W. Kidd (e), J. A. Knauss (e), L. Lek (e), R. M. Lesser (ce), R. G. Mason (abdefh), G. F. McEwen (ceg), W. H. Munk (beh), P. Osborn (e), P. H. Ottosen (e), F. B. Phleger (e), R. W. Raitt (abceh), N. W. Rakestraw (eg), R. R. Revelle (cefgh), R. W. Rex (abcdefgh), A. F. Richards (ef), M. K. Robinson (e), P. Rudnick (e), M. B. Schaefer (e), F. P. Shepard (befh), G. G. Shor, Jr. (beh), W. G. Van Dorn (e), G. H. Volkmann (e), W. S. Wooster (e)
Lake Hughes--O. R. Rudder (c)
La Mesa--J. B. Smyth (bc)
La Mirada--V. Vanni (eg)
Lodi--F. H. Watson, Jr. (cg)
Lomita--J. C. Alter (cg)
Lompoc--P. R. Nixon (cg)
Long Beach--R. S. Brown (fg), W. A. Kelly (dfgh), W. L. Knight (bdeh), F. Kunkel (g), D. H. McKillop (g), F. F. Mead (abeg), F. S. Riley (g)
Los Altos--D. R. Schink (e), S. H. Williston (d)
Los Banos--H. A. Stoddard (g)
Los Angeles--D. Alter (c), E. H. A. Andrews (abh), H. P. Bailey (c), D. M. Baker (g), P. Baumann (cg), R. J. Bean (abh), J. A. B. Bjerknes (c), H. F. Blaney (g), G. L. Brown (bde), M. F. Burke (cg), S. S. Butler (g), G. Buto (b), G. V. Chilingar (eg), R. Y. D. Chun (ceg), D. E. Cole (cg), H. Conkling (eg), W. H. Cook (abgh), J. C. Crowell (cegh), C. J. Derrick (b), F. J. Doran (cg), C. Durrell (fh), R. P. Eckis (bg), J. G. Edinger (c), C. C. Elder (cg), K. O. Emery (de), F. F. Friend (g), H. P. Gates (d), R. M. Glendinning (gc), M. Glicken (ad), D. S. Gorsline (ef), B. S. Grant (g), U. S. Grant (eg), C. H. Gregory (abh), D. T. Griggs (abfh), J. E. Halferty, W. A. Hall (g), S. E. Helprin (bd), R. B. Hickok (g), W. I. Hicks (g), R. A. Hill (g), W. Hofmann (g), J. Holmboe (c), W. T. Holser (fh), R. E. Holzer (cd), H. W. Hoylman (bdfh), M. R. Huberty (g), C. B. Hussey (e), J. J. Jakosky (ad), E. J. Johnston (g), H. K. Kallmann (cd), J. Kaplan (cd), R. Y. Kawano (g), J. E. Kilkenny (bdh), F. O. Klein (d), L. Knopoff (bd), S. J. Kriz (h), W. A. Lang (cg), C. T. Leeds (beg), D. J. Leeds (b), H. B. Lynch (g), J. F. Mann, Jr. (g), J. T. McGill (efgh), Y. Mintz (c), L. K. Morris (ab), S. B. Morris (bcg), M. Neiburger (ce), W. L. Orr (efgh), C. E. Palmer (c), F. S. Parker (bdh), J. G. Parker (bdh), Ralph M. Parsons Co. (J. E. Halferty, representative), A. F. Pillsbury (g), H. K. Pratt (cg), W. C. Putnam (abcefg), H. P. Roth (c), R. E. Rule (bcfgh), H. Salvatori (b), W. L. Sanders (abfh), Z. Sekera (ce), H. N. Shepard (g), L. B. Slichter (abdh), L. D. Statham (abcd), R. Stone (befgh), G. S. Tapley (g), K. V. Taylor (abgh), R. D. Terry (e), G. Tuneli (fh), E. Uchupi (eg), K. Q. Volk (bcg), H. O. Westby (g), S. A. Wilfong (cg)
Lynwood--D. H. Wozab (eg)
Madera--H. Barnes (g)
Martinez--G. C. Ralls, Jr. (eg)
McClellan Air Force Base--A. P. Whipple (abh)
Menlo Park--G. D. Bath (d), L. D. Clark (d), F. A. Donath (h), R. S. Gomes (g), S. W. Grinnell (g), C. F. Hains (g), D. F. Hewett (fg), A. M. Hietanen-Makela (fh), D. H. Hutchison (c), M. C. Israelsky (eg), S. Katz (bdeh), P. B. King (bh), H. B. Kinnison (cg), H. E. Kuehn (d), A. Locke (fh), R. S. Lord (g), P. L. Magill (abcdefgh), C. W. Merriam (h), A. M. Piper (g), T. C. Poulter (abd), R. G. Reeves (df), T. W. Robinson (cg), W. S. T. Smith (befgh), N. H. Stearn (dh), H. E. Thomas (g), D. E. White (fgh), D. G. Willis (abdgh)
Merced--N. A. MacGillivray (g), K. R. McSwain (g)
Modesto--F. R. Reynolds (ag)
Mojave--O. J. Backus (bcg)
Montebello--M. B. Scott (g)
Monterey--W. D. Duthie (c), C. L. Taylor (ce), W. C. Thompson (abce), J. B. Wickham (ce)
Mountain View--A. L. Aden (cd)
North Highlands--J. R. Moran (bd)
North Hollywood--M. Anderson (g), G. A. Brown (g), C. J. Dommes (g), J. Paull (abceg), H. B. Shapiro (cg), I. Sherman (ag)
Northridge--J. C. Fredericks (g)
Oakland--R. M. Dreyer (abdfh), M. R. Lewis (g), C. H. Sandberg (adfh), W. V. Stauder, S. J. (bcd)
Oak View--D. C. Pontius (bcefg)
Oildale--J. A. Mann (bh), C. A. Bengtson (abcdefgh), G. S. Hilton (fg)
Orange--H. G. Ferris (de), R. C. Timme (e)
Orcutt--J. J. McCullough (d)
Oxnard--W. A. Bowen, Jr. (d), C. Mock (b), J. T. O'Brien (eg)
Pacific Palisades--W. W. Kellogg (cd), D. E. Whelan, Jr. (ade)
Pacoima--J. T. Williams (c)
Palo Alto--W. E. Bell (dh), H. Forbes (g), C. V. Givan (cg), L. M. Henry (c), R. L. Ives (cg), S. M. Jones (bdefh), A. H. Lachenbruch (bcefgh), R. K. Linsley (g), C. R. Longwell (abefh), G. M. MacLeod (bg), V. E. McKelvey (degh), S. E. Rantz (g)
Palos Verdes Estates--R. I. Meeker, Jr. (c)
Parks Air Force Base--J. W. Mixsell (cg)
Pasadena--J. C. Arnold (bd), H. Benioff (bh), C. S. Benson (bdfh), N. H. Brooks (g), H. S. Brown (ef), I. Campbell (cfgh), T. J. Chow (eg), R. F. Clawson (g), F. R. Cline (cg), C. H. Dix (abdh), T. R. Fahy (eh), E. A. Flinn, III (b), J. I. Gimlett (abdfh), J. R. Grady (e), B. Gutenberg (abcdefgh), G. W. Housner (b), A. C. Ingersoll (eg), R. H. Jahns (fgh), R. E. Kennedy (cg), R. T. Knapp (ceg), F. B. Laverty (cg), G. S. Leopold (eg), H. A. Lowenstam (ef), P. B. MacCready, Jr. (cg), J. E. McKee (g), R. B. Moran, Jr. (bdh), B. T. Morris (g), J. M. Nordquist (abcfh), W. C. Peterson (g), G. W. Potapenko (ad), F. Press (abdefh), W. H. Rempel (c), C. F. Richter (bh), R. P. Sharp (fg), E. L. Smith (g), R. G. Sohlberg, (bfh), A. L. Sonderegger (eg), V. A. Vanoni (g), T. von Karman (ceg), W. O. Wagner (ag), H. O. Wood (abfh), O. R. Wulf (cd), F. Zwicky (dgh)
Piedmont--R. P. Cook (cg), O. W. Swainson (bde)
Pinole--K. J. Walsh (ceg)
Pomona--V. S. Aronovici (cg)
Porterville--I. H. Althouse (g), F. A. Strauss (g)
Rancho Santa Fe--G. C. Ewing (ceg)
Redding--M. T. Saylor (ag)
Redlands--J. A. Battle (c), B. Dibble (g), E. F. Dibble (cdg), H. P. Hinckley (g), J. J. Prendergast (g)
Red Mountain--D. L. Gardner (g),

Redwood City--S. M. Barnes (g), T. R. Dosch (g)
Reseda--J. T. Pettit (ab)
Richmond--R. B. Krone (g)
Riverside--T. B. Barnidge (c), H. L. Creason (g), M. Donnelly (cg), J. H. Dorroh, Jr. (g), M. Fireman (g), L. A. Richards (cgh), S. J. Richards (g), L. H. Stolzy (cg), L. V. Wilcox (g)
Sacramento--C. W. W. Abbott (cg), B. A. Arnold (ceg), T. L. Atherton (ae), V. W. Bacon (g), H. O. Banks (gh), V. W. Barth (g), R. T. Bean (g), L. R. Beard (cg), V. Bengal (g), J. I. Burns (cg), G. R. Carroll (g), W. D. Fuqua (bg), W. I. Gardner (fg), A. Givan (cg), C. O. Greenwood, Jr. (abcdefgh), J. M. Haley (g), J. B. Hammon (ag), L. K. Hill (ghc), C. P. Holdredge (befg), W. H. Holmes (ad), M. Kramsky (g), C. H. Kromer (bfh), B. E. Lofgren (ceg), P. J. Lorens (eg), L. H. Magar (aceg), E. C. Marliave (g), C. R. McClure, Jr. (g), J. M. Morris, Jr. (ag), M. E. Murphy (g), J. Osoffsky (g), D. S. Pastir (g), J. B. Paulson, Jr. (cg), J. F. Poland (gh), E. P. Price (cdg), D. T. Prophet (c), R. C. Richter (g), R. R. Rowe (cg), W. G. Schulz (g), W. B. Shaw (g), E. W. Silitch (g), H. M. Stafford (g), D. S. Stoner (g), A. C. Swanson (g), R. O. Thomas (cg), F. L. Thompson (cg), J. van de Erve (cg), I. W. Walling (g), E. P. Warren (g), C. M. Weber (g), R. A. Williams (ag), H. D. Wilson, Jr. (g), P. R. Wood (g), G. F. Worts, Jr. (g), A. L. Zimmerman (cg)
Salinas--E. C. Jahr (abg)
San Bernardino--J. V. Hastings (bd), W. P. Rowe (g)
San Bruno--G. B. Marchand (abcdefgh), R. C. Nichols (c)
San Diego--S. S. Ballard (df), R. J. Baron (e), G. L. Bloom (eg), B. Brooks (fg), A. L. Brosio (cg), J. H. Brown (bdh), E. C. Buffington (aefgh), A. J. Carsola (efh), M. F. Culbertson (ce), R. G. Fawcett (c), A. B. Focke (bcde), E. E. Gossard (ce), E. L. Hamilton (e), E. C. LaFond (c), E. M. Little (bcde), W. K. Lyon (e), J. J. Marciano (ceg), J. G. Pattullo (ce), J. L. Reid, J Jr. (e), G. P. Rigsby (g), J. F. T. Saur, Jr. (ce), G. A. Shumway (ae), C. R. Sparger (ce), E. W. Thatcher (bcdeh), J. F. Wingo (g)
San Francisco--B. S. Barnes (cg), A. G. Bartlett (eg), R. C. Bundgaard (c), California Research Corp. (N. A.Riley, representative), G. Corwin (fh), D. B. Doan (eh), C. E. Everson (c), H. L. Foster (ch), M. A. Garbell (cde), R. Y. Grant (fg), H. Green (bfg), R. B. Hall (ah), G. H. Hargreaves (g), W. M. Jaekle (abceg), M. V. Jiranek (cg), P. Joralemon (f), O. Kehrlein (g), W. S. W. Kew (beh), H. Kramer (g), G. A. LaRocque, Jr. (g), C. H. Lee (g), T. J. Maher (abdeh), A. R. McBirney (f), D. H. McLaughlin (efgh), T. H. Means (bcg), H. J. Miles (eg), R. C. Miller (ceg), A. L. Morris (cg), C. A. Palmer, Jr. (ce), G. A. Peers (g), J. W. Peoples (fh), A. R. Platzer (c), J. Reber (g), D. F. Rex (abcegh), R. Rhoades (fgh), J. S. Sandberg (c), S. G. Sargis (dh), I. J. Silverstone (g), T. R. Smith (g), W. Stava (cg)
San Gabriel--D. Baron (g), A. E. Bruington (g), L. L. Longacre (g), J. L. Merriam (cg), R. C. Taylor (cde)
San Jose--R. C. Briggs (g), F. R. Hall (g), E. E. Stohsner (ab)
San Luis Obispo--T. E. Wales, Jr.
San Marino--H. Hoover, Jr. (abcdefgh), W. Littlefield (g), R. W. Spencer (agh), C. M. Swinney (fh), K. van der Weg (bfh)
San Mateo--H. M. Moses (ag), W. W. Steen (g), J. A. Stirton (ae), H. S. Wahlen (a)
San Rafael--R. E. Jentoft, Jr. (ce)
Santa Ana--E. A. La Bahn (cg), M. N. Thompson (cg)
Santa Barbara--R. D. Elliott (c), R. E. Evenson (fg), S. R. Frank (c), K. S. Muir (g), N. R. Williams (bcdegh)
Santa Clara--E. E. Harris (g), A. I. Mei, S.J. (b), J. A. Weber, S.J. (bc)
Santa Monica--J. C. Bose (ae), D. Deirmendjian (c), R. R. Rapp (c), J. D. Sartor (c), E. H. Vestine (bcdh)
Santa Rosa--R. B. Cozzens (g)
Sebastopol--J. Kittredge (g)
Sherman Oaks--G. L. Arnold (cg)
Soda Springs--K. R. Knoerr (g)
South Laguna--L. de Witte (bdh)
Stanford--S. N. Davis (cgh), L. E. Eber (c), J. B. Franzini (acg), R. A. Helliwell (d), K. L. Hunkins (bdh), A. Knopf (fh), E. B. Knopf (fh), K. B. Krauskopf (fh), L. A. Manning (cd), B. M. Page (bfgh), J. L. Soske (bcdfh), S. G. Taylor, Jr. (b), G. A. Thompson (h), J. K. Vennard (g), C. M. Walter (eg)
Stockton--G. W. Fuller (eg),
Sunset Beach--N. R. Shade (abcdeh)
Tarzana--J. W. Rolston (ceg)
Temple City--R. C. Crooke (e)
Three Rivers--R. H. Rose (bcfg)
Travis Air Force Base--T. C. Jafferis (c)
Upland--N. W. Burr (b), R. V. Ward (g)
Van Nuys--R. J. Havens (d), J. E. Slosson (eg)
Ventura--T. L. Bailey (abefh), R. H. Jamison (g), A. S. Rummelsburg (ceg), F. F. H. Wang (abdefgh)
Vista--L. G. Boyd (bceg) 56
West Covina--R. G. Thomas (defgh)
Whittier--J. H. Brown (g), C. G. Gunnerson (eg), M. L. Hill (h), C. J. Leith (fh), E. E. Moots (gh), J. F. Riccio (abdegh), W. J. Wood (cg)
Yreka--G. R. B. Elliott (dfh)

Canal Zone

Balboa--E. Kanz (abcg), E. H. Marx (c), R. H. Stewart (eh)
Fort Clayton--R. F. Geller, Jr. (ad)

Colorado

Arvada--R. A. Clark (ceg), W. P. Fulton (cg), F. C. Koopman (g), I. S. McQueen (g), C. R. Miller (g)
Boulder--W. C. Bradley (eg), J. W. Broxon (d), P. W. Carlin (bc), W. B. Chadwick (acdh), W. S. Cooper (g), R. M. Davis, Jr. (d), F. E. Fowler, G. A. Gamow (adh), T. N. Gautier, Jr. (d), W. D. George (a), S. C. Gladden (cd), W. S. Hough (dg), H. H. Howe (d), R. W. Knecht (d), H. I. Leighton (d), J. V. Lincoln (d), H. E. Malde (gh), Mount Sopris Instrument Corp. (F. E. Fowler, representative), K. A. Norton (acd), F. E. Roach (d), W. O. Roberts (cd), A. H. Shapley (bdh), R. J. Slutz (d), T. L. Thompson (bcegh), E. E. Wahlstrom (fh), L. A. Warner (fh), M. L. White (d), V. Withstandley, III (abcdefgh), K. R. Wright (g), O. E. Youngdahl (d)
Broomfield--R. S. Foote (d)
Climax--H. C. Wells (bdh)
Denver--T. P. Ahrens (cfgh), J. Amorocho (cg), G. G. Anderman (befgh), H. A. Aurand (cd), J. H. Baily (g), F. B. Barker (fg), W. A. Beetem (g), G. C. Bennet (ceg), F. A. F. Berry (be), R. A. Black (bd), G. L. Blinde (cg), M. F. Boos (fh), W. M. Borland (acg), R. Bowman (bdh), A. J. Broscoe (g), E. R. Brumbaugh (b), R. S. Cannon, Jr. (efh), W. D. E. Cardwell (g), G. H. Chase (gh), W. C. Chenoweth (abd), L. W. Crow (c), R. C. Culler (cg), B. F. Curtis (cgh), M. E. Denson, Jr. (abdefgh), C. E. Dobbin (befh), J. P. Dolan (bdgh), G. R. Downs (bf), F. C. Frischknecht (abdgh), W. U. Garstka (cg), J. Gilluly (abefgh), R. E. Glover (bg), L. O. Grant (c), W. R. Griffitts (fh), R. F. Hadley (eg), O. C. Hansen (g), G. E. Harbeck, Jr. (cg), R. M. Hazlewood (b), J. D. Hem (g), J. C. Hollister (b), R. C. Holmer (bd), I. E. Houk (bcg), J. P. House (b), W. H. Irwin (fgh), D. J. Jameson (abcdefgh), A. F. Johnson (g), O. Kalmbach (g), G. V. Keller (d), E. C. King (g), N. J. King (g), I. P. Krick (c), J. M. Lara (g), H. Larson (cg), B. F. Leonard, III (dfh), S. W. Lohman (g), G. A. Macdonald (bfh), W. C.

Lovering

MacQuown, Jr. (abd), C. R. Maierhofer (ag), T. G. McLaughlin (fgh), K. R. Melin (g), J. S. Meyers (cg), S. A. Miller (g), M. Mozayeny (g), J. M. Nash (h), J. C. Olson (fh), F. W. Osterwald (fh), R. M. Pearl (af), H. V. Peterson (bcg), H. A. Powers (f), G. M. Richmond, (acdgh), H. S. Riesbol (cg), B. N. Rolfe (g), E. Rose (bcg), G. Rouse (bh), E. M. Schlaikjer (ab), K. B. Schroeder (g), S. A. Schumm (g), F. R. Shawe (fh), J. F. Smith, Jr. (efgh), G. L. Snyder (befh), R. L. Sprinkel, Jr. (gh), N. C. Stone (c), R. J. Tipton (cg), S. W. Totten (bdh), F. L. Travis (abdh), T. D. Trostle (b), D. S. Turner (abefgh), M. C. Van Lewen (acg), D. J. Varnes (fh), W. W. Wheeler (g), R. E. Wilcox (dfg), T. C. Wilson (abch), R. A. Wise (b)
Durango--W. F. Burke (bdf), W. F. Crabtree (bdfg), B. F. Latch (abh), W. J. Osterhoudt (beg), K. G. Smith (bdg)
Englewood--G. A. Hill (egh)
Evergreen--J. W. Steverson (c)
Fort Collins--M. L. Albertson (cg), T. E. Bridge (dfh), T. L. Broin (efgh), J. E. Cermak (ag), A. R. Chamberlain (cg), W. E. Code (g), N. A. Evans (g), B. C. Goodell (cg), D. V. Harris (fgh), M. D. Hoover (g), J. L. Kovner (cg), E. W. Lane (ceg), L. D. Love (g), P. K. Mohanty (g), D. F. Peterson (acg), E. V. Richardson (g), C. Rohwer (g)
Golden--J. J. Bradley (b), D. F. Coolbaugh (abdh), T. L. Finnell (abfgh), A. J. Gude, III (bcdfh), S. P. Kanizay (bfh), R. B. Morrison (bgh), M. A. Omar (abd), P. A. Rodgers (d), S. S. Shannon, Jr. (cefgh), J. W. Vanderwilt (fh)
Grand Junction--H. E. Brown (g), F. M. Byers, Jr. (f), J. E. Case (abdfh), R. C. Cutter (abefgh), D. P. Elston (fg), J. W. Gabelman (fh), R. D. Goodrich (g), P. R. Guinn (bcdgh), R. A. Laverty (bd), F. C. Merriell (cg), A. T. Miesch (fh), D. A. Phoenix (g), C. H. Roach (befgh), E. M. Shoemaker (fh), J. D. Strobell, Jr. (abdfgh), D. G. Wyant (dfh)
Gunnison--H. K. Rouse (g)
Lafayette--F. E. Moore (fh)
Lakewood--J. R. Cooper (abfh), R. Hamburger (adfh), G. E. Koberg (g), T. S. Lovering (defgh), G. W. Walker (abfh)
Littleton--Ohio Oil Co. (P. M. Konkel, representative), R. D. Russell (abcdefgh), G. O. Veneklasen (bf)
Pueblo--K. E. Ireland (g)
Sterling--R. Monahan (b)
Wheat Ridge--F. A. Bertle (g), M. E. Bunger (ag), H. P. Eisenhuth (g), A. I. Johnson (g), J. M. Terry (g), R. J. Winger, Jr. (g)
Woodland Park--H. W. Berndt (cg)

Connecticut

Bridgeport--F. L. Panuzio (acgh)
Canaan--W. D. Lambert (abeh)
Danbury--A. L. Lange (g)
Hamden--C. L. W. Swanson (cg)
Hartford--W. R. Hamon (c), T. F. Malone (c), C. M. Saville (cg)
Madison--A. J. Boucot (h)
Middletown--R. V. Cushman (fgh), J. L. Rosenfeld (fh)
New Haven--A. M. Bateman (acfg), G. Breit (d), D. Brouwer (a), C. O. Dunbar (c), R. F. Flint (ceg), E. D. Hoffleit (cd), M. L. Jensen (afgh), G. A. Riley (e), G. Robley (cg), J. Rodgers (fh), P. B. Sears (abcdefgh), K. K. Turekian (ef), G. K. Voigt (g), M. S. Walton, Jr. (bdefh)
Norwalk--C. K. Panish (acegh)
Orange--L. C. Graton (fh)
Pomfret--B. O'Brien (cd)
Quaker Hill--E. B. Rothenberg (be)
Ridgefield--E. H. Boissonnas (bd), H. G. Doll (d), T. E. Stewart (d)
Riverside--E. T. Simmons (g)
Rowayton--A. E. Buller (h)
Storrs--J. M. Aitken (fh), J. B. Lucke (beh), K. C. Tippy (acgh), A. N. Vanderlip (ag)
Tariffville--J. H. Thomas (c)
West Hartford--B. L. Bigwood (g)
West Haven--J. E. Sanders (fhe)
Westport--G. E. Wheeler (g)
Wethersfield--R. L. Carnahan (cg)
Windsor Locks--D. Hackett (g), C. D. Hopkins, Jr. (g), W. E. Ray (cg)

Delaware

Newark--A. C. Barlow (g), D. H. Boggess (g), G. F. Collins (ceg), J. J. Groot (eg), D. E. Outlaw (g), V. L. Pearson, Jr. (eg), W. C. Rasmussen (bcg)
Wilmington--J. L. Gillson (fg), E. L. Hockman (abdefgh)

District of Columbia

Washington--C. G. Abbot (c), P. H. Abelson (aef), L. H. Adams (bdfh), L. B. Aldrich (cd), L. T. Aldrich (f), A. G. Alexiou (c), C. O. Alexis (abcdefgh), A. S. Allen (bdgh), L. P. Allen (cdeg), C. A. Anderson (fh), J. R. Anderson (c), M. J. Andre (c), G. E. Andreasen (cg), A. W. Andrews (d), W. H. Atwood, Jr. (ab), J. E. Ayres (abde), L. F. Bailey (b), A. A. Baker (fgh), R. G. Baker (b), A. H. Balak (a), J. R. Balsley, Jr. (dh), F. B. Barkalow (g), F. H. Barry (a), J. M. Barry (acdgh), W. N. Bascom (e), C. C. Bates (bce), H. Bay (ae), J. L. Beatty (gh), R. R. Bennett (g), J. M. Berdan (g), F. A. Berry (c), S. F. Bershad (efh), R. R. Bodle (bh), L. D. Bonham (h), C. D. Bonnot (c), N. F. Braaten (a), J. N. Bradley (cg), J. T. Breen (c), M. Brenner (abcdefgh), C. L. Bretschneider (c), G. W. Brier (cg), L. J. Briggs (aef), D. W. Bronk (ex officio), L. E. Brotzman (ceg), G. F. Brown (fg), R. H. Brown (g), T. T. Brown (de), L. M. Brush, Jr. (cegh), C. D. Bue (cg), P. B. Bunton (abcdefgh), W. S. Burbank (fh), E. B. Burwell, Jr. (bfgh), P. E. Byerly (bdeh), B. C. Byrnes (d), J. M. Caldwell (eg), J. B. Campbell (abd), D. S. Carder (bdfh), H. H. Carter (ce), G. D. Cartwright (c), F. W. Cater, Jr. (fh), N. H. Chavasse (c), F. Chayes (fh), W. Chimiak (e), J. F. Clark (d), A. L. Cochran (g), C. W. Cochrane (c), G. V. Cohee (de), L. O. Colbert (abde), W. D. Collins (g), H. J. Coolidge (abcdefgh), E. L. Corton, Jr. (c), R. C. Counts, Jr. (c), B. K. Couper (e), J. S. Cragwall, Jr. (g), K. G. Crosby (ae), F. L. Culley (a), E. S. Cullings (g), R. N. Culnan (ceg), R. L. Cushman (gh), T. Dalrymple (cg), R. F. Dearduff (e), P. S. De Leonibus (ce), J. H. Dellinger (d), L. P. Disney (e), C. A. Douglas (c), A. A. Drake, Jr. (bfh), R. F. Dressler (ceg), M. D. Dubrow (g), J. T. Duce (abd), J. A. Duerksen (a), D. C. Duncan (f), A. v. V. Dunn (g), D. L. Durham (h), T. E. Eakin (g), R. O. Eaton (eg), C. F. Ellingwood (a), G. H. Espenshade (fh), W. B. Eyestone (cg), F. S. Farquhar (e), A. T. Fernald (c), J. G. Ferris (g), A. G. Fiedler (g), H. E. Finnegan (e), G. FitzGerald (a), F. J. Flynn (cg), P. D. Foote (bgh), A. Forch (a), S. Fritz (c), C. L. Garner (abde), A. A. Garrett (g), I. E. Gaskill (a), R. D. Geisenderfer (ce), V. D. George (a), J. J. Glass (f), J. W. Graham (bfh), J. W. Greig (bf), S. B. Grenell (a), M. S. Griffin (g), P. W. Guild (fh), R. B. Guillou (fg), C. L. Gunn, Jr. (bdfh), R. Gunn (cdfh), J. T. Hack (g), N. R. Hagen (c), W. H. Haggard (c), F. Hall (ce), J. V. Hall, Jr. (eg), W. T. Hammond (e), D. L. Harris (ced), L. P. Harrison (c), J. C. Harrold (g), W. W. Hastings (g), J. H. Hawley (e), J. F. Hellweg (abcd), A. E. Helmers (cg), H. W. Hemple (ae), R. G. Henderson (ad), E. L. Hendricks (g), J. P. Heppner (bcdh), J. Hershberger (abdh), W. E. Hiatt (cg), C. W.

Hoffer (abh), J. Hoffman (ae), A. J Hoskinson (ah), W. G. Hoyt (cg), R. C. Hubley (cg), E. O. Hulburt (de), P. A. Humphrey (c), M. N. Hunter (c), L. Hurwitz (abd), W. H. Hymes (c), D. M. Ilch (g), E. Ingerson (fh), H. Insley (fh), C. F. Izzard (g), W. C. Jacobs (ceg), H. L. James (df), P. E. Jamison (aefgh), W. A. Jenner (cg), H. R. Joesting (dfh), A. Johnson (g), D. S. Johnson (c), P. M. Johnston (gh), B. E. Jones (bdg), J. W. Joyce (bdh), L. V. Judson (ab), M. F. Kane (ab), O. Kaufman (beh), H. W. Keith, Jr. (abe), R. B. Kennard (c), G. H. Keulegan (g), E. R. King (bdh), H. B. Kinnison (g), S. S. Kirmani (g), E. Klein (b), D. W. Knoll (ceg), W. J. Kotsch (c), G. M. Krahl (cg), S. P. Kramer (abceg), P. H. Kratz (ae), R. F. Kresge (cg), F. J. Lacny (c), H. E. Landsberg (bch), W. B. Lang (egh), W. B. Langbein (abcdefgh), W. S. Lanterman (c), E. S. Larsen, Jr. (f), E. S. Larsen, III (f), E. O. Larson (a), G. Leifson (ae), L. B. Leopold (g), J. M. LeRoy (cde), V. Lewicke (acd), F. Lewis (ceg), G. G. Lill (abcdefgh), D. M. Little (c), W. H. Littlewood (e), K. E. Lohman (efh), S. K. Love (g), J. Lyman (e), K. A. MacKichan (g), T. Maddock, Jr. (g), G. E. Manger (aefgh), H. Marcus (bh), J. Marcus (ce), W. Markowitz (a), W. Marks (ce), A. H. Mason (ag), A. C. Mason (g), J. C. Mathisson (e), A. E. Maxwell (e), P. A. Mazeika (e), A. L. McCahan (adeg), C. H. McCurdy (d), C. C. McDonald (g), R. J. McGough (ceg), C. L. McGuinness (g), E. T. McKnight (f), M. C. McLean (e), B. K. Meade (a), G. Medina (ae), H. E. Merwin (ef), J. L. Meuschke (d), H. A. Meyerhoff (bfgh), D. L. Mills (a), C. L. Mitchell (c), G. S. Mitchell (c), J. M. Mitchell, Jr. (bcf), E. V. Mohl (ade), W. L. Molo (c), A. R. Mooney (befg), R. W. Moore (bdg), T. S. Moorman, Jr. (c), H. F. Morey (g), H. R. Morgan (a), G. E. Morris, Jr. (ae), R. M. Moxham (a), V. S. Murino (cg), L. M. Murphy (bcfh), C. R. Murray (g), W. Mussetter (a), J. Namias (c), P. F. Narten (g), R. B. Neuman (abdh), F. Newhall (cg), D B. Newlin (a), D. R. Nichols (fgh), T. B. Nolan (fh), H. Odishaw (cd), J. E. O'Hare (ce), H. W. Oliver (abdeh), H. Orlin (a), W. C. Overstreet (fh), B. L. Page (a), R. M. Page (c), E. J Parkin (ac), J. L. H. Paulhus (c), C. G. Paulsen (g), A. D. Peterson (bcdg), B. J. Peterson (g), G. Phair (fh), J. O. Phillips (abde), C. Pierce (ae), C. T. Pierson (fh), C. S. Piggot (ef), A. C. Poling (a), D. C. Ports (d), W. D. Potter (g), G. C. Prescott, Jr. (g), M. S. Quraishy (aceg), J. C. Rabbitt (f), M. C. Rabbitt (bfh), C. E. Ramser (g), H. S. Rappleye (a), L. L. Ray (cg), E. W. Reed (g), J. C. Reed (f), F. W. Reichelderfer (c), F. J. Reynolds, Jr. (a), D. A. Rice (a), L. Riches (e), E. P. Richey (cg), M. Rigby (eg), R. E. Riordan (a), I. E. Rittenburg (ae), E. B. Roberts (abde), E. W. Roedder (f), F. Ronne (abcdefgh), A. Rosenbloom (cgh), C. S. Ross (f), C. W. Ross (e), W. W. Rubey (efgh), L. H. Rumbaugh (bdeh), S. Ruttenberg (d), T. V. Ryan (e), I. T. Sanders (ae), W. S. Sands (e), T. Saville, Jr. (e), A. N. Sayre (g), T. M. Schad (g), J. F. Schairer (f), M. H. Schefer (e), P. L. Schereschewsky (cd), W. G. Schlecht (fh), R. W. Schloemer (cg), E. Schmid (a), R. G. Schmidt (f), W. L. Schmitt (e), A. H. Schooley (ce), P. Schureman (e), D. C. Scull (abd), R. W. Seaton (d), C. R. Seeger (abcdefh), A. L. Shalowitz (e), C. A. Shelton (a), G. R. Shelton (a), E. R. Shepard (bh), J. Sherrod, Jr. (c), A. J. Shneiderov (bd), W. Shofnos (ae), M. Siegrist (befh), L. G. Simmons (a), T. Skowron (a), J. B. Small (a), J. W. Smith (bde), V. B. Smith (abg), W. E. Smith (abcdefgh), W. M. Smith (cd), L. J. Snell (g), J. L. Speert (ag), H. C. Spicer (bdfh), J. T. Stark (befh), P. P. Starke (ce), R. B. Starr (e), J. L. Stearn (a), W. F. Steiner (d), V. T. Stringfield (g), V. Suvannooss (ad), B. Swenson (cg), H. L. Swift (c), G. S. Switzer (f), C. Symns, Jr. (a), I. R. Tannehill (ceg), H. Tatel (abcdefh), E. A. Taylor (a), L. L. Thatcher (eg), T. P. Thayer (fh), C W. Thomas (e), H. G. Thomasson (eg), E. S. Thompson (cg), G. R. Tilton (f), M. S. Tischler (fh), R. Tousey (cd), J. I. Tracey, Jr. (efh), F. W. Trainer (g), T. K. Treadwell, Jr. (de), A. P. Trei (abe), L. B. Tuckerman (dh), M. A. Tuve (d), F. W. van Straten (c), E. M. Vernon (c), R. B. Vice (g), R. L. Viets (ad), H. H. Waesche (bf), C. L. R. Walke (g), L. F. Warrick (g), C. B. Watts (a), G. M. Watts (eg), T. J. Wehe (ceg), L. L. Weiss (cg), F. G. Wells (fgh), H. W. Wells (cd), C. A. Whitten (a), A. H. Williams (g), W. T. Wilson (cg), J. W. Winchester (ce), K. J. Winiarski (cg), J. S. Winston (c), W. E. Wrather (acefg), H. S. Yoder, Jr. (cef), B. D. Zetler (e)

Florida

Coral Gables--F. Chew (ce), L. F. Conover (cg), H. W. Hiser (acg), J. D. Richard, Jr. (be), V. G. Sleight (befh), F. G. W. Smith (e), G. E. Wagoner (bcd), M. P. Wennekens (e)
Daytona Beach--C. W. Parker (c)
Eau Gallie--A. R. Beach (d)
Eglin Air Force Base--H. W. Leaf (abcdefgh)
Fort Lauderdale--W. D. Mason (cg), J. C. Stephens (g), H. T. Stetson (abcdeh)
Gainesville--P. Bruun (e), K. D. Butson (cg), C. G. Edson (cg), M. H. Latour (cd), W. H. Pierson (c), D. B. Smith (g)
Jacksonville--R. L. Anderson (c), E. W. Eden, Jr. (g), C. E. Elmore (cg), N. Enge (g), L. A. Farrer (cg), T. E. Haeussner (ceg), E. H. Miller (g), W. N. Moreland (cg), C. L. Nowlin (g), R. G. Plaster (c)
Lakeland--H. G. Stewart, Jr. (g), W. S. Wetterhall (beg)
Largo--H. S. Shaw (acde)
Lynn Haven--K. L. Sherman (cdh)
Miami--G. E. Dunn (ce), H. Klein (g), F. A. Kohout (g), P. Sollenberger (a)
North Miami--F. F. Pilotte (bc)
Ocala--E. Brown (g)
Opa Locka--M. H. Gilmore (bdh)
Orlando--B. J. Sherry (c), W. H. Twenhofel (abe)
Panama City--G. B. Austin, Jr. (e), F. D. Sisler (e)
Patrick Air Force Base--R. F. Durbin (cg), C. E. Ewing (ac), J. C. Tison, Jr. (a)
Pensacola--T. L. Lowery (cg), W. E. Moore (eh)
St. Andrew--G. B. Dowling (e)
St. Augustine--B. J. Bermes (abdeg)
St. Petersburg--G. R. Woodring (a)
Sarasota--H. Arctowski (cefh), A. G. Matthews (eg)
Tallahassee--W. A.Baum (ceg), J. S. Beazley (a), H. H. Cooper, Jr. (g), W. A. Dryden (ceg), T. A. Gleeson (c), H. Gunter (adeg), S. L. Hess (c), F. C. W. Olson (e), M. I. Rorabaugh (g), S. L. Rosenthal (c), W. F. Tanner (cegh)
West Palm Beach--O. O. Fickeissen (acg), A. W. Johnson (ceg), S. D. Owen (a), F. B. Schmittker (a), R.H. Simpson (c)

Georgia

Albany--J. H. Carlson (ag)
Americus--J. L. Ferguson (c)
Athens--R. L. Bowen (abdefgh), H. Clark (g)
Atlanta--M. R. Carstens (g), J. J. George (c), B. M. Hall, Jr. (cg), E. S. Harrison (cg), D. B Jones (g), C. P. Lindner (g), M. T. Thomson (g), R. L. Wait (g)
Augusta--W. E. Fox (cg), H. Raynes (cg)
Dillard--D. E. Whelan (abcdefgh)
Emory University--W. H. Grant (f), J. G. Lester (fh)
Forest Park--L. P. Gibbon (a)
Gainesville--W. E. Hardy (c)
Grantville--G. D. Pritchett, Jr. (ad)
Hapeville--D. W. Miller (c)

Macon--W. H. Miller (c)
Moody Air Force Base--G. H. Lynn (ac)
Savannah--H. B. Counts (g)
Tifton--L. R. Mills, Jr. (ag)

Guam

Agana--S. Valenciano (g)

Hawaii

Ewa--M. L. Cleven (bde), L. R. Southwick (abd)
Hawaii National Park--J. P. Eaton (bf), C. K. Wentworth (eg)
Honolulu--T. S. Austin (e), L. D. Baver (g), H. W. Brodie (c), R. B. Campbell (g), J. Chu (cg), R. K. Chun (abg), D. C. Cox (fgh), J. B. Cox (g), R. H. Cox (g), D. A. Davis (gh), P. C. Ekern, Jr. (cg), R. P. Hall (abcdefgh), G. T.Hirashima (cg), H. S. Leak (g), J. W. McGary (ceg), J. F. Mink (efg), H. S. Palmer (bfg), H. D. Parry (c), M. O. Rinkel (ce), G. R. Seckel (eg), K. J. Takasaki (eg), B. D. van't Woudt (g), H. A. Wadsworth (g), G. Yamanaga (g)
Kekaha--G. Y. Ewart (g)
Lanikai--R. R. Griswold (g)
Paia--R. H. Taylor (cg)

Idaho

Boise--H. A. Allen (befgh), K. E. Anderson (fgh), H. C. Fletcher (fgh), H. D. Hafterson (cg), G. W. Kirkpatrick (g), M. R. Kulp (g), H. Meisler (bfgh), Z. E. Mills (g), M. J. Mundorff (cgh), M. W. Nelson (g), W. R. Wagner (fh)
Idaho Falls--H. L. Hamilton, Jr. (c)
Kingston--B. F. Dickerson, III (fh)
Moscow--C. C. Lomas, Jr. (acg), C. C. Warnick (g)
Pocatello--D. W. Brown (bdf), A. Isotoff (f)

Illinois

Barrington--J. C. Bellamy (c)
Batavia--J. Bruin (g)
Carbondale--S. E. Harris, Jr. (eg), H. M. Morris (cgh)
Centralia--J. L. Lester (h)
Champaign--W. S. Daniels (g), R. G. Godfrey (cg), F. A. Huff (c), L. A. Joos (ceg), W. D. Mitchell (g), E. J. Monke (g), J. H. Morgan (g), W. J. Roberts (cg), N. L. Rupani (cg), G. E. Stout (cg)
Chicago--B. Ackerman (cdeg), E. W. Barrett (c), L. J. Battan (c), R. G. Berk (cg), H. A. Brown (ce), H. R Byers (ceg), J. W. Dixon (g), D. R. Fitzgerald (cd), J. R. Fulks (c), D. Fultz (c), J. C. Jamieson (bdfh), J. E. Jenkins (b), R. F. Kilmartin (bcg), V. A. Koelzer (cg), D. S. H. Louie (g), M. A. Melton (g), L. E. Miller (abcdefgh), Y. Nakagawa (cde), W. H. Newhouse (f), C. W. Newton (c), M. S. Paul (c), S. Petterssen (ce), R. S. Platt (c), J. Radner (c), H. Riehl (c), J. Rosinski (cf), R. J. Roth (c), A. R. Schmitt, S.J. (b), R. L. Slater, Jr. (c), H. C. Urey (aeh), T. Wasson (abdg), J. C. Weil (c), G. F. White (g), J. F. Wiss (bg), R. Wright (fh)
DeLand--J. L. Hubbard (c)
Effingham--H. H. Luttrell (bf)
Evanston--A. Assur (ceg), R. B. Banks (cg), E. E. Bergman (dh), J. B. Cullison, Jr. (c), E. C. Dapples (eg), W. S. Hamilton (cg), A. L. Howland (f), W. C. Krumbein (ceg), L. H. Nobles (gh), A. Ogata (g), J. O. Osterberg (bg), C. B. Reynolds (bdfh), H. A. Slack (f), L. L. Sloss (eh)
Fort Sheridan--H. A. Hubbard (eh)
Glenview--R. W. Gerdel (cg)
Kappa--R. K. Morse (bg)
Lemont--H. Moses (c)
Moline--L. A. Carlson (g), L. W. Dick (cg), W. A. Joern (cg)
Mount Carmel--C. S. Sharp (a)
Northbrook--B. L. Hansen (cg)
Olney--K. G. Boling (ab)
Ottawa--H. Y. Fang (bg)
Paxton--H. W. Schwartz (c)
Peoria--D. H. Schnepper (bg)
Riverside--R. R. Braham, Jr. (c)
Robbs--W. R. Boggess (g)
Rolling Meadows--K. J. Zentner, Jr. (g)
Skokie--H. J. Dorman (b), E. B. Shykind (g)
Springfield--W. J. Andrews (g), T. B. Casey (g), L. C. Christensen (c), R. F. Spanski (eg)
Streator--C. N. Johnston (g)
Urbana--W. C. Ackermann (cg), R. E. Aten (g), C. A. Bays (bg), A. H. Bell (dh), W. F. Bradley (fh), M. B. Buhle (dg), V. T. Chow (g), D. U. Deere (eg), J. J. Doland (g), J. C. Frye (g), J. C. Guillou (g), J. E. Hackett (g), J. L. Hough (egh), P. W. Hughes (g), A. Klute (g), W. F. Lytle (cg), G. B. Maxey (g), H. Mynlieff (h), M. W. Pullen (dh), J. M. Robertson (ceg), F. Sargent, II (c), M. O. Schmidt (ah), J. A. Simon (fg), H. F. Smith (g), J. B. Stall (g), R. R. Storm (dg), M. Suter (g), E. Townley (bcd), H. R. Wanless (bcefgh), G. W. White (g), J. D. Winslow (bdgh)
Wilmette--H. Bader (g), J. E. Gillis, Jr. (gh), A. Higashi (cg), H. F. Lawhead (abc)

Indiana

Bloomington--R. F. Blakely (bcd), J. Mead (bd), S. S. Visher (cg)
Columbus--G. F. Hendricks (g)
Elkhart--W. F. McDonald (ceg)
Evansville--S. W. Rampy (cg), H. Simmons (cg), J. R. Warren (bdf)
Greencastle--C. L. Bieber (bc)
Hanover--C. Adams (abcdefgh)
Indianapolis--W. A. Bertrand (c), M. C. Boyer (g), J. I. Perrey (g), C. M. Roberts (fgh), W. H. Walker (g)
Lafayette--K. S. Curtis (a), J. W. Delleur (g), D. Swartzendruber (cg)
Notre Dame--A. J. MacAlpin (bcefgh)
Paoli--S. H. Murdock, Jr. (gh)
South Bend--S. Kolupaila (g)
Terre Haute--R. H. F. Pao (g)
Valparaiso--A. W. Manning (d)
West Lafayette--A. S. El-Naggar (g), J. D. Hume (eg), R. L. Schuster (bfgh)
Whiting--F. C. Roop (cg)

Iowa

Ames--G. L. Barger (cg), G. W. Fox (bcd), R. K. Frevert (cg), C. S. Gwynne (bfgh), H. P. Johnson (g), D. Kirkham (cg), J. Lemish (efh), R. V. Ruhe (fgh), R. H. Shaw (cg)
Coralville--E. C. Pogge (g)
Council Bluffs--J. V. Barnes (fg)
Des Moines--R. I. Bucknell (abd), C. R. Elford (cdeg), C. E. Lamoureux (c), J. A. Power, Jr. (cg)
Hull--M. Maasland (cg)
Iowa City--F. M. Dawson (cg), H. G. Hershey (cfgh), R. A. Hoppin (cefh), J. W. Howe (g), H. J. Koloseus (ceg), E. M. Laursen (g), C. J. Posey (g), J. J. Runner (fh), A. C. Tester (eg), A. C. Trowbridge (cefgh), J. A. Van Allen (cd)
West Branch--W. J. Blackburn, III (ab)

Kansas

Fredonia--W. L. Stryker (adfh)
Lawrence--L. F. Dellwig (fh), V. C. Fishel (c), F. C. Foley (g), P. C. Franks (fh), R. H. King (eh), C. W.

Liberal--L. W. Stewart (d)

Manhattan--W. S. Chepil (cg), N. P. Woodruff (cg)

Merriam--R. A. Sanders (c)

Norton--M. L. Thompson (cg)

Prairie Village--J. P. McCallister (g), H. C. McComb (bcg)

Salina--W. D. Waterman (g)

Topeka--L. W. Furness (cg), R. A. Garrett (acg), J. E. Schrock (abcdefgh)

Wichita--J. R. Berg (fh), R. R. Brewer, Jr. (bdh), R. B. Hofmann (bdh), K. G. Redman (abcdefgh), G. J. Stramel (g), P. J. Van Altena (bfh), R. F. Walters (gh)

Kentucky

Danville--R. Ellis (ce)

Fort Thomas--J. W. Bruce (bg)

Lexington--J. W. Huddle (eg), K. O. Lange (c), A. C. McFarlan (bh), P. McGrain (g), J. A. Shear (ce)

Louisville--O. K. Anderson (c), L. E. Carroon (g), W. S. Conaway (g), F. B. Harkness (cgh), R. W. Kellogg (g), A. A. Lane (c), W. E. Price, Jr. (g), F. F. Schrader (g), W. Stosser (cg), A. F. Thiele (cg)

Paducah--T. W. Lambert (bh), L. M. Mac Cary (g)

Williamsburg--C. H. Minehan (g)

Louisiana

Alexandria--R. Newcome, Jr. (eg), H. L. Pree, Jr. (bg)

Baton Rouge--H. B. Brown, Jr. (abcefgh), C. O. Durham, Jr. (abcefh), F. N. Hansen (g), H. N. Harrison, Jr. (aeg), J. W. Higgs, Jr. (g), H. V. Howe (abdefgh), H. J. Howe (h), J. Huner, Jr. (eh), H. E. Kleinpeter, Jr. (aeg), J. W. Lipscomb (d), A. E. McGrew (c), R. R Meyer (g), G. E. Murray (abe), C. K. Oakes (g), L. M. Odom (cg), W. J. Randolph (cg), R. J. Russell (acegh), R. J. Smith (h), E. J. Taylor (cg), A. M. Van Tyne (b)

Donaldsonville--H. L. Stille (ce)

Houma--G. Augustat (b)

Lafayette--R. L. Beh (abcdefgh)

New Iberia--D. H. Warren (abde)

New Orleans--G. I. Atwater (bh), F. A. Benedetto, S.J. (d), R. B. Brockhouse (e), G. M. Byrum (ce), W. H. Diment (abdh), J. B. Farr (b), A. H. Glenn (ceg), C. F. Grubb (bh), E. H. Harlow (eg), D. W. Hullinghorst (cg), W. S. Pike, Jr. (bfh), F. E. Simmons, Jr. (bg), W. L. Stapp (a), J. F. Waldron (g)

Pineville--A. H. Harder (g)

Shreveport--G. L. Baker (dh), B. W. Blanpied (befh), P. A. Bloomer, Jr. (bh), C. L. Bryan (abcdefgh), J. M. Forgotson (bdfh), R. T. Hazzard (abefh), C. J. Husum (abdh), D. T. MacRoberts (cg), H. I. Meyer, H. A. Morriss, Jr. (dh), R. R. Rosenkrans (bfh), United Gas Corp. (H. I. Meyer, representative), C. N. Valerius (h), W. C. Wagner (bc)

Vidalia--R. A. Campbell (bde)

Maine

Augusta--M. R. Stackpole (g)

Kittery--R. N. Williams (e)

North Bridgton--E. Smith (c)

Orono--J. M. Trefethen (fgh), L. A. Wing (h), E. S. Wood, Jr. (a)

Portland--C. Chibka (cg), P. A. Lutz (ce)

Prospect Harbor--C. F. Merriam (g)

Waterville--T. Moore (ac)

Wilton--W. M. Adams (bh)

Maryland

Aberdeen--W. H. Townsend (bc), W. D. Weart (bh)

Aberdeen Proving Ground--W. W. Berning (c), B. Perkins, Jr. (abcdfh), A. A. Thompson (bc)

Adelphi--W. J. Dichtel (d), R. Gornitzky (a), G. H. Ward (g)

Accokeek--W. L. Petrie (bdefg), R. G. Stone (cg), J. Q. Tierney (e)

Annapolis--M. Duffy (bcdeg), R. E. Kent (e), P. V. H. Weems (ae), J. Williams (e)

Army Chemical Center--S. D. Thayer (c)

Baltimore--C. F W. Anderson (d), G. S. Benton (ceg), M. K. Blaustein (fgh), P. Bock (cg), D. E. Carritt (e), G. D. Colchagoff (df), R. D. Coons (c), J. P. Delaney, S.J. (bcdh) H. H. Engelbrecht (g), F. C. Farnham (dh), J. H. Fox (abdh), O. Gates (ef), J. C. Geyer (ceg), G. A. Guy, Jr. (c), E. J. Harned (g), B. Holzman (cg), J. J. Kramp (a), D. A. Mazzarella (c), M. J. Pollak (ace), D. W. Pritchard (ce), C. E. Renn (e), W. H. Rhodes (d), C. A. Richardson (g), I. Roman (abdh), S. L. Russak (cg), J. W. Siegmund (eg), J. T. Singewald, Jr. (abfgh), T. H. Slaughter (eg), W. D. Sutcliffe (ah), J. H. Swartz (abcdefgh), A. C. Waters (bfh), A. Wolman (cg)

Bel Air--G. H. Milly (c), J. D. Wilcox (cg)

Beltsville--T. W. Edminster (g), V. H. Jones (g), L. L. Kelly (cg), L. E. Myers, Jr. (cg), W. H. Sammons (cg), D. D. Smith (g), D. W. Swanson (ceg), W. S. White (h)

Bethesda--H. K. Armstrong (g), L. M. Branscomb (d), H. L. Cook (bcg), A. L. Day (bfh), P. C. Doran (abde), J. H. Eberly (c), R. D. Fletcher (ceg), H. W. Frantz (abcdefgh), R. C. Grubb (cg), C. Harmantas (c), H. A. Karo (abde), C. E. Lewald (g), J. E. McCall (ag), E. C. McKay (ae), B. S. Melton (b), R. L. Nace (gh), T. J. Nordenson (g), L. C. Peltier (c), V. D. Rockney (c), C. F. Romney (b), W. H. Simonson (acg), H. C. Storey (cfg), H. S. Thomas, Jr. (g), O. W. Torreson (d), A. O. Waananen (g), L. K. Wenzel (g), R. M. Wilson (a), D. R. Woodward (g)

Burtonville--C. L. Parsons (d)

Cabin John--E. M. Sodano (a)

Capitol Heights--C. H. Swick (aeh)

Cheverly--W. S. Davis (ac), B. E. Olson (ce), J. H. Willett (aeh)

Chevy Chase--M. E. Brown (a), M. F. Burrill (c), J. J. Capello (d), B. Frank (g), R. S. Goodridge (cg), W. C. Hendrix (de), E. A. Johnson (dh), H. F. Johnston (abcdefgh), H. S. Ladd (ef), P. H. Lowry (c), G. D. Lukes (cd), M. A. Mason (eg), J. A. O'Keefe (a), R. H. Randall (ae), J. M. Symons (e), R. H. Weightman (c), G. D. Whitmore (a), M. G. Wolman (g), E. G. Zies (ef)

Clinton--M. D. Burkhart (ce), M. M. Cook (ae)

College Park--J. M. Burgers (befh), H. W. Hobbs, Sr. (cg), F. S. Jory (d), F. F. Le Fever (g), S. F. Singer (d), H. C. S. Thom (cg), W. L. Tressler (e)

Conowingo--R. E. Turner (cg)

District Heights--R. J. Alexander (ae), O. S. Lee (e)

East Riverdale--W. C. Spreen (cg)

Gaithersburg--E. L. Williams (a)

Garrett Park--F. L. Weaver (g)

Greenbelt--E. W. Coffay (g), W. H. Klein (c)

Hyattsville--H. G. Bitting (a), L. A. Cole (e), C. H. Hardison (cg), G. A. Hathaway (cgh), K. M. Nagler (c), G. C. Sherlin, Jr. (cdg), A. B. Taylor (g), R. N. Wilson (g), A. J. Zmuda (d), R. T. Zoch (cg)

Kensington--L. R. Alldredge (d), J. L. Crone (cd), R. W. Davenport (g), R. C. Doolittle (abdfh), H. W. Jaffe (f), H. E. Newell, Jr. (cd), L. R. Page (f), R. C. Peavey (d), R. L. Rector (eg), H. G. Snay (e), B. W. Wilcox (e)

Landover Hills--H. W. Dubach (ceg)

Lanham--C. S. Scofield (g)

Linthicum Heights--O. Njus (c)

Long Green--H. T. Orville (c)

Mount Rainier--L. Pavlides (befh)

Owings Mills--F. W. Lee (abcdefgh)

Riva--B. Kinsman (e)
Riverdale--D. J. Keen (e)
Rock Hall--C. D. Greene (ce)
Rockville--J. S. Beers (a), H. E. Cronin (bd), H. M. Frazier (c), T. I. Gray, Jr. (c), J. F. Miller (cg), R. P. Savage (e)
Ruxton--R. M. Overbeck (g)
Severna Park--R. E. Hanson (bcd)
Silver Spring--C. B. Brown (g), B. H. Chovitz (a), W. L. Cowan (ag), W. J. Dempsey (d), H. G. Dorsett, Jr. (de), W. I. Duvall (bh), H. N. Eaton (eg), G. T. Faust (bf), A. L. Forest (c), F. N. Frenkiel (ce), L. M. Glymph, Jr. (g), M. S. Gurnee (ceg), E. A. Hogge (d), M. Hooker (fh), E.-Y. Hsu (g), R. P. Ireland (g), R. A. Jachowski (abefgh), B. L. Johnson (abcdefgh), M. Katzin (cde), D. G. Knapp (d), M. A. Kohler (cg), J. A. Kuhn, Jr. (abcd), W. W. Lamoreux (cg), B. J. Lieske (ceg), E. Lipson (d), W. Malkin (bcdeg), J. M. Martin (b), D. P. Martineau (ce), V. Mockus (cg), N. A. Pore (ce), R. Raspet (bcdf), C. W. Reck (g), B. S. Richmond (e), E. C. Robertson (h), E. O. Schonstedt (d), H. E. Schwarz (g), W. O. Smith (dgh), C. Swigart (g), R. A. Warner (fgh), H. C. Woster (cg)
Suitland--J. F. Andrews (c), P. F. Clapp (c), A. R. Clark (ce), E. J. Saltsman (c)
Takoma Park--I. Fischer (a), W. E. Maloney (e), A. L. Shands (ceg), B. L. Snavely (be)
Towson--E. Cloos (bfh)
Tracy's Landing--L. A. Bloom (a)
Upper Marlboro--E. M. Hulburt (e)
Washington Grove--L. E. Shmidl (a)
West Hyattsville--R. H. Woessner (cd)
Wheaton--J. N. Adkins (bd)
Woodbine--D. B. Krimgold (g)

Massachusetts

Amherst--A. Arons (ce), G. A. Marston (acg), G. W. Webb (abcdefgh)
Arlington--E. T. Allen (f), R. A. Minzner (c), C. H. Pierce (c), K. C. Spengler (ceg)
Bedford--C. E. Anderson (c), E. J. Chernosky (bcd), E. L. Eaton (c), P. G. Goldberg (cd), N. Goldstein (abe), G. A. Knapp (abd), N. A. Orsini (b), H. K. Sen (cd), I. Solomon (c), P. H. Wyckoff (d)
Belmont--D. F. Barnes (bdefh), M. Greenberg (c), E. Radner (c), R. H. Woodward (d)
Beverley Farms--T. H. Leith (dh)
Boston--E. A. Blackey, Jr. (cgh), R. O. Castle (bh), R. A. Craig (cde), I. B. Crosby (bcefgh), W. P. Elliott (ce), O. M. Hackett (efg), H. N. Halberg (g), N. Herz (fh), J. E. Hobson (bd), P. F. Howard (g), L. Katz (d), C. A. Kaye (efh), C. E. Knox (g), Chas. T. Main, Inc. (B. O. McCoy, representative), B. O. McCoy, M. D. O'Day (cd), J. W. Raymond, Jr. (g), H. M. Turner (g), W. F. Uhl (g), R. M. White (ceg), E. A. Wilder (cg), L. M. G. Wolman (cg), G. K. Wood (g)
Bridgewater--P. Huffington (c)
Brighton--E. Maple (d)
Brookline--F. L. Olmsted (g)
Cambridge--E. R. Anderson (cdeg), H. B. Bigelow (e), M. P. Billings (afh), F. Birch (bfh), D. C. Blanchard (ce), B. T. Bower (cg), P. W. Bridgman (b), A. Casagrande (g), J. G. Charney (ce), G. L. Clarke (e), R. A. Daly (bfh), R. R. Doell (d), J. P. Downs (bd), P. S. Eagleson (eg), G. M. Fair (g), H. W. Fairbairn (fh), F. L. Foster (bd), C. Frondel (h), R. M. Garrels (h), D. R. F. Harleman (eg), N. A. Haskell (bh), H. G. Houghton (ce), P. M. Hurley (fh), A. T. Ippen (eg), W. B. Joyner (d), G. J. F. MacDonald (bfh), T. R. Madden (abdeh), K. F. Mather (befh), H. E. Mckinstry (fh), D. H. Menzel (d), J. P. Miller (fg), H. B. Pettit (cd), N. A. Phillips (c), R. C. Sagalyn (d), R. L. Sax (abdegh), G. F. Schilling (cd), B. Shorr (ce), R. R. Shrock (efgh), H. A. Thomas, Jr. (g), J. B. Thompson, Jr. (fh), S. Treitel (bdfh), D. v. Z. Wadsworth (bdefh), F. L. Whipple (ac), W. L. Whitehead (h), H. C. Willett (ce), G. R. Williams (g), J. W. Winchester (f)
Carlisle--N. G. Parke, III (d)
Cochituate--P. C. Dalrymple (ce)
Concord--A. C. Bemis (c), A. E. Benfield (h), G. W. Dyer (dg), P. Newman (cd)
Danvers--M. A. Miller (c)
Framingham--T. D. N. Douthit (bd)
Holbrook--C. E. Lee (e)
Holden--L. J. Hooper (g)
Jamaica Plain--D. L. Arenberg (c)
Lexington--J. E. Gallagher (c), W. E. Howell (c), C. F. Jenkins (c), C. E. Junge (c), C. B. Moore (dc)
Lincoln--D. W. Mann (ac)
Lynnfield--H. C. Alberts (cd)
Malden--W. S. Butcher (efh)
Marblehead--D. M. Ferguson (abcdefgh), F. Sanders (c)
Marshfield--E. R. Snow (ceg)
Medford--I. I. Schell (ce), C. E. Stearns (fg)
Melrose--E. Dews (ce)
Milton--C. F. Brooks (ceg), E. J. Clasby (c), S. P. Fergusson (cg), J. H. O'Mara (efgh)
Natick--W. B. Anderson (c), D. H. Miller (cg), H. H. Rasche (c), W. F. Wood (abcdefgh)
Newton--O. Tenenbaum (c), E. W. Wahl (c)
Newton Highlands--A. P. G. Peterson (acd)
Newtonville--H. H. Lettau (cdeh)
North Abington--J. F. McClay (d)
Northampton--M. Schalk (ce)
North Scituate--B. Vonnegut (c)
Quincy--S. B. Solot (cg)
Reading--A. E. Tancreto (ce)
Roxbury--I. M. Browne (ce)
Scituate--R. E. Huschke (c), K. Maynard (ce)
South Dartmouth--H. E. Cramer (c)
South Duxbury--R. M. Field (abcdefgh)
South Hadley--M. V. Woodland (cf)
South Lincoln--N. C. Gerson (cd), J. Katzenstein (d)
Sudbury--J. G. Wolbach (d)
Walpole--V. G. Plank (c)
Waltham--M. L. Barad (c), S. C. Coroniti (cd), J. A. Peoples, Jr. (bdeh), T. F. Rogers (bcdgh)
Watertown--W. Baginsky (ceg), J. G. Bryan (c), D. Skidmore (de), J. B. Wiesner (d)
West Medford--R. L. Nichols (f)
West Newton--C. W. Wolfe (befgh)
Weston--W. Blake, Jr. (cefgh), G. Leblanc, S.J. (bg), D. Linehan, S.J. (abh)
West Springfield--R. F. Novotny (efgh)
West Tisbury--H. Hotchkiss (abcdefgh)
West Yarmouth--R. D. Cotell (abcdefgh)
Williamstown--F. Foote (bef), W. I. Milham (cdg), E. L. Perry (bfh)
Woburn--H. G. Healy (g)
Woods Hole--L. H. Barbour (ae), D. F. Bumpus (e), E. T. Bunce (e), C. E. Carver, Jr. (ceg), J. Chase (ce), R. S. Edwards (abe), H. G. Farmer, Jr. (eg), D. H. Frantz, Jr. (e), F. C. Fuglister (e), J. B. Hersey (abdh), B. H. Ketchum (e), W. V. Kielhorn (e), R. A. Lufburrow (e), A. R. Miller (e), J. E. Murray (e), A. C. Redfield (e), F. A. Richards (e), W. S. Richardson (e), M. S. Rutstein (e), M. Sears (e), E. H. Smith (ceg), P. F. Smith (e), F. M. Soule (de), H. Stommel (e), A. C. Vine (ae), W. S. von Arx (ce), A. H. Woodcock (e)

Michigan

Ann Arbor--R. L. Belknap (cgh), A. Blake (bdeh), E. F. Brater (g), L. I. Broggs, Jr. (bcfh), R. Choate (bfg), D. H. Clements (bdeh), R. E. Dils (g), D. F. Eschman (befgh), R. C. Fitzpatrick (abcdefgh), E. N.

Goddard (f), E. W. Heinrich (f), E. W. Hewson (c), R. C. Hussey (ae), J. R. Kramer (f), K. K. Landes (efg), J. S. McNown (eg), E. H. Poindexter (fgh), C. F. Powers (e), A. Spengos (cg), F. S. Turneaure (f), J. T. Wilson (bch), C. O. Wisler (g), J. H. Zumberge (eg)
Battle Creek--N. FitzSimons (abdfgh)
Bloomfield Hills--L. J. Bulkley (cf)
Calumet--J. P. Pollock (f)
Clare--T. H. McConica, III (cgh)
Dearborn--M. Ference, Jr. (cdh)
Detroit--F. A. Blust (g), L. V. Garrity (g), F. C. Go (eg), L. R. Hafstad (d), W. T. Laidly (ag), H. Mandelbaum (ceg), W. H. Parsons (fh)
East Lansing--R. A. Baltzer (eg), A. H. Eichmeier (c), A. E. Erickson (g), F. D. Freeland, Jr. (cg), G. H. Hautau (abdh), H. R. Henry (g), W. G. Keck (d), E. H. Kidder (g), J. W. Trow (gh)
Grand Rapids--E. M. Burt (efgh), P. E. Johnson (c)
Grosse Pointe Farms--J. W. Mulford (f)
Houghton--L. O. Bacon (abdf), J. Fisher (bcd), W. A. Longacre (bdgh), J. M. Neilson (h), W. H. Parrott (ce), A. K. Snelgrove (bf), D. G. Yerg (cdg)
Iron Mountain--G. B. Patrick (c)
Ishpeming--B. H. Boyum (abcdefgh)
Kalamazoo--R. A. Sanderson (dg)
Lansing--T. Abrams (a), E. Derragon (bcg), J. G. Rulison (cg), S. W. Wiitala (g)
Mount Pleasant--G. C. Sleight (abd)
Negaunee--W. J. Hinze (abdefh)
Pontiac--H. W. Dodson (d), R. R. McMath (adh)
Ypsilanti--D. J. Portman (c), N. Smith (d), D. E. Willis (beh)

Minnesota

Duluth--H. J. Hakala (ad), E. D. Johnson (dg), J. Royce (d)
Minneapolis--A. G. Anderson (g), J. C. Craddock (bdefh), D. M. Davidson (d), J. L. Gergen (cd), S. S. Goldich (f), G. O. Guesmer (ag), J. M. Harris (bdfh), L. A. Johnson (g), H. A. Jongedyk (g), P. W. Kenworthy (c), D. B. Lawrence (cfg), A. F. Meyer (cg), H. M. Mooney (abdfh), M. M. Newman (cd), A. D. Nicolaou (bd), E. B. Sandell (f), D. F. Soland (abd), A. F. Spilhaus (ce), L. G. Straub (g), J. H. Strub, Jr. (cg), J. S. Sumner (abdfh), H. E. Wright, Jr. (cegh)
Northfield--L. M. Gould (gh), D. Stewart (f)
Rochester--A. L. Orvis (cd)
St. Paul--W M. Bollenbach (g), B. R. Colby (cg), W. S. Glock (cefg), C. L. Larson (g), S. M. Rubens (d), M. E. Nelson (aeg), R. Schneider (g), R. L. Schreurs (dgh)

Mississippi

Biloxi--N. M. Burgner (c)
Brookhaven--J. E. Barthelemy, Jr. (b)
Ellisville--C. R. Pettis (g)
Greenville--J. G. Joern (c)
Hattiesburg--O. T. Brown (f), H. J. Richgels (abd)
Jackson--G. V. Fish (ceg), J. W. Lang (g), B. Mather (fh), K. Mather (efh), R. R. Phillips (b), R. B. Spencer (abcde), W. W. Sykes (abg)
Laurel--Z. W. Falcone (eg)
Ocean Springs--G. Gunter (eg)
Starkville--J. C. McWhorter (cg)
State College--H. v. H. Flinsch (ceg), A. W. Raspet (bcdh)
University--R. Woodburn (ag)
Vicksburg--F. B. Campbell (cg), M. J. Hvorslev (eg), N. R. Moore (cgh), W. E. Rater (cg), W. H. G. Roth (cg), R. A. Tobiaski (g), E. J. Williams, Jr. (g)

Missouri

Brentwood--G. K. Hasegawa (g)
Buckner--R. E. Johnson (g)
Clayton--J. R. Stinson (c)
Columbia--D. A. Bradley (fh), R. B. Curry (cg), W. L. Decker (cg), P. W. Fletcher (g), V. C. Jamison (g), W. D. Keller (fh), W. M. Sangster (cg), R. Z. Whipkey (g), H. W. Wood, Jr. (g), C. M. Woodruff (g)
Granby--J. T. Bradford (bd)
Kansas City--V. Alexander (g), W. R. Astleford (g), E. C. Balke (ceg), J. A. Browne (c), L. P. Hahn (cg), V. G. Marty, Jr. (cg), R. Morgan (cg), A. C. Neumann (ceg), W. L. Northrop (cg), D. E. Phillips (cg), R. J. Theisen (cg), H. J. Thompson (g), C. F. Van Thullenar (ceg), N. T. Veatch (g), R. F. Warner (g)
Lee's Summit--H. E. Erickson (cg)
Normandy--R. N. Craig (cg)
Overland--G. Stallard (c)
Rolla--G. C. Amstutz (fh), H. C. Bolon (g), G. B. Clark (b), C. G. Edwards (begh), O. R. Grawe (efg), W. C. Hayes (fg), D. Kennedy (a), J. V. Lavery (dfh), J. C. Maxwell (bg), M. S. Petersen (g), J. P. Roston (bg), R. Ruch (bde)
St. James--J. T. Sturm (cg)
St. Louis--V. J. Blum (abcdh), G. Braught (b), J. C. Brice (eg), E. M. Brooks (ceg), F.-K. Chang (abd), M. J. Colvin, Jr. (b), J. P. Condaxis (cg), J. J. Connor, Jr. (b), A. J. Frank (bdfg), E. J. A. Gain (g), R. F. Hautly (b), R. R. Heinrich (bc), N. S. Hinchey (bg), P. M. Honnell (b), W. W. Horner (cg), S. W. Jens (g), F. Klein (ag), P. Light (cg), O. S. Maker (abcdeg), R. G. Mann (cg), L. D. McGinnis (b), H. F. Mondschein (cg), O. W. Nuttli (ab), H. M. Reitz (gh), W. H. Roschke, Jr. (bcdgh), L. Scharon (bdfgh), D. A. Schulz (bgh), G. J. Vencill (cg), D. P. Venker (befg), J. A. Volk (bd), A. L. Worseck (cg)
University City--C. Kisslinger (abdh)
Whiteman Air Force Base--P. R. Stinchfield (c)

Montana

Big Timber--D. E. Burnham (bdef)
Billings--P. Greenlee (b), R. A. Harris (bch), R. H. Howe (bdefh), L. J. Larguier (b), A. C. Munyan (abcdefgh), J. W. Peters (abdh), H. Porter, Jr. (abdh), H. L. Thomsen (ab)
Bozeman--C. C. Bradley (fh), E. R. Dodge (cg)
Butte--B. W. Brown (fh), F. L. Koucky (ah), S. W. Nile (b)
Fort Peck--T. F. Carr (g)
Great Falls--A. F. Bateman, Jr. (gh), E. P. Beaulieu (abcefgh), C. E. Erdmann (fgh)
Helena--R. A. Dightman (c), C. S. Heidel (g), N. J. Holter (e)
Missoula--J. H. Dieterich (abcdefg), P. Ingebo (g), P. E. Packer (cg), R. B. Smith (ceg), R. W. Wilke (g)
Wolf Point--C. G. Congdon (abcdefgh)

Nebraska

Bellevue--M. H. Sipple, Jr. (ceg), C. K. Wilcox (c)
Columbus--R. S. Clark (cg)
Grand Island--J. F. Mayne (cg)
Hastings--J. A. Allis (g)
Lincoln--P. C. Benedict (g), R. G. Bowman (c), F. L. Duley (cg), O. H. Gish (cdfh), S. G. Heidel (g), H. G. Heinemann (cg), C. H. Hembree (efg), D. W. Hubbell (g), J. C.Jensen (cd), C. F. Keech (g), K. M. Kent (g), R. F. Kreiss (g), R. H. Langford (g), A. L. Lugn (cg), A. P. Mazurak (g), D. S. McVicker (g), E. C. Reed (g), O. J. Scherer (g), E. F. Schramm (cef), W. R. Stevens (c), G. H. Taylor (g)

Omaha--A. L. Alin (abcefg), J. M. Barton (abh), D. C. Bondurant (cg), L. C. Fowler (cg), M. E. Kirby (bdfgh), E. W. McClendon (ceg), R. J. Pafford, Jr. (cg), J. A. Reinemund (bh), E. F. Stapowich (ce), R. N. Towl (g), O. B. Van Horn (cg), T. Waara (g)

Nevada

Boulder City--F. S. Anderson (g), F. K. Illk (g), H. E. Pelham (cg)
Carson City--W. Arnold (a)
Minden--G. M. Dangberg (cg)
Reno--H. P. Boardman (g), J. E. Church (ceg), N. S. Hall (g), W. E. Long (acg), E. M. P. Lovejoy (bdfgh), L. S. McGirk, Jr. (adg), V. I. Myers (g), J. T. Ryan (g), V. E. Scheid (fh), J. F. Wall (c)

New Hampshire

Concord--W. R. Fuller (g)
Dublin--R. Sagendorph (a)
Durham--J. A. Lockwood (dc), T. R. Meyers (fg), C. J. Schneer (af)
Exeter--C. M. Matthews (acg)
Goffstown--J. V. Salo (cdg)
Hanover--A. L. Washburn (cg)
Laconia--K. H. Beij (g), R. S. Sartz (g), G. R. Trimble, Jr. (g)
West Lebanon--J. B. Lyons (f)

New Jersey

Allendale--A. M. Lunetta (cg)
Alpine--S. Paige (abg)
Asbury Park--A. Arnold (c), H. Weickmann (cdg)
Atlantic City--S. Deitch (c)
Bloomfield--R. M. Schotland (cde)
Bridgeton--J. R. Mather (c), J. R. Randolph (cg), I. Remson (g), T. E. A. van Hylckama (g)
Cape May Court House--T. C. Nelson (ceg)
Colonia--W. E. Eggert (c)
East Orange--D. L. Floras (b), S. Katz (bd)
Elizabeth--J. H. Sanford (g)
Elmer--C. W. Thornthwaite (cg), S. J. Ware (cg)
Fair Haven--F. H. Dickson (d)
Fort Monmouth--G. A. Wolff (c)
Freehold--H. J. aufm Kampe (c)
Haddonfield--K. E. Andrews (bcd)
Hillside--H. Levy (cg)
Jersey City--J. E. Christopher (abcdefgh)
Leonia--H. R. Aldrich (dfh)
Little Ferry--A. R. Pagan (cg)
Little Silver--L. A. Pick (cd)
Maplewood--J. M. Robbins (ag)
Metuchen--J. C. F. Tedrow (g)
Montville--E. B. Douglas (bdh)
Murray Hill--W. A. Marrison (a)
Neptune--D. M. Swingle (cd)
New Brunswick--H. Johnson (eg), G. Winchester (ch)
Orange--K. Yu (g)
Parlin--G. L. E. Linn (g)
Pennington--R. E. Cyphers, Jr. (g)
Princeton--W. E. Bonini (abdh), A. F. Buddington (fh), K. S. Deffeyes, G. B. Hess (abcdeh), H. H. Hess (abefh), H. D. Holland (f), S. B. Irish (a), P. Kissam (a), T. A. Konigsmark (eh), J. C. Maxwell (bdfh), E. Sampson (fh), L. Spitzer, Jr. (cde), J. C. Stewart (h), W. T. Thom, Jr. (abdfh), G. Veronis (ce), H. F. Winterkorn (cg)
Princeton Junction--R. Vajk (abdh)
Ridgewood--L. A. Leyenberger (cg)
South Orange--H. A. Foster (g)
Trenton--H. C. Barksdale (cg), J. A. Bettendorf (acg), D. F. Dougherty (g), C. H. Gaum (g), M. E. Johnson (abdg), G. R. Shanklin (cg)
Upper Montclair--H. E. Hallborg (d), N. van der Sleen (abdfh)
West Caldwell--R. A. Wilkens (g)
Westfield--H. R. Magnuson (bfg), R. B. Sosman (fh), C. H. Voelker (ceg)
Woodbury--A. B. Andrews (b)
Wood Ridge--A. W. Wakeling (c)

New Mexico

Alamogordo--C. S. Bagley (a), J. G. Jones (cd), M. W. Jones (bcdh), F. O. Rossmann (cdegh), E. A. Steinhoff (ac)
Albuquerque--J. H. Abrahams, Jr. (fg), F. C. Ames (g), L. J. Bjorklund (g), J. W. Blagbrough (ef), J. G. Breiland (c), R. H. Carter, Jr. (cg), B. N. Charles (cde), C. S. Conover (cg), J. B. Cooper (g), P. Donnerstag (abdfh), E. J. Dortignac (cg), R. W. Fife (g), E. D. Gordon (g), R. L. Griggs (fg), J. W. Hood (g), C. E. Hyvarinen (g), S. Italia (abd), D. Johnstone (cg), F. W. Kennon (g), R. E. McKown (ce), T. O. Meeks (g), P. E. Melancon (fgh), B. T. Mitchell (cg), G. L. Oakland (g), W. R. Perret (bd), J. W. Reed (c), C. V. Theis (g), F. D. Trauger (g), J. E. Weir, Jr. (g), S. A. Wengerd (abefh)
Carlsbad--J. W. Miller (b), W. E. Pratt (bcefg)
Deming--L. T. Putnam (g)
Hachita--R. A. Zeller, Jr. (ah)
Hobbs--E. C. Woodruff (befh)
Holloman Air Force Base--M. M. Hopkins, Jr. (c)
Las Cruces--W. J. Brown (c), F. V. Hansen (c)
Los Alamos--T. J. Boyd, Jr. (cd), H. T. Gittings, Jr. (cdeh), B. T. Rogers, Jr. (ag), L. Sherman (c)
Roswell--R. Crandall (dh), S. E. Galloway (g), L. B. Haigler (g), R. D. Holt (abegh), R. W. Mower (acg), R. E. Murphy (gh)
Santa Fe--P. D. Akin (g), D. E. Kienlen (g), Z. E. Spiegel (g), C. B. Thompson (g), J. C. Yates (g)
Socorro--A. J. Budding (bfh), S. J. Buckwold (fg), F. X. Bushman (efh), W. D. Crozier (bd), R. H. Frische (abcdfgh), F. E. Kottlowski (dfh), F. J. Kuellmer (fh), M.-S. Sun (fh), V. Vacquier (abcd), M. H. Wilkening (cd), M. E. Willard (fh), E. J. Workman (d)
State College--W. C. Barrett (cg)

New York

Akron--R. A. Brown (c)
Albany--D. B. Bogart (g), H. D. Brice (g), J. J. Cassidy (cde), J. R. Crippen (g), B. Dunn (g), W. E. Forrest (g), I. G. Grossman (bfh), A. W. Harrington (cg), R. C. Heath (cg), E. D. Hendricks (acg), T. Isaacs (fgh), F. K. Mack (bg)
Amawalk--S. F. Kelly (abcdfh)
Babylon--G. V. Pesce (cg)
Bayside--A. D. Henderson (eg), A. F. Merewether (c)
Boonville--L. Lansing (c)
Bronxville--B. J. Dunn (d)
Brooklyn--W. L. Donn (ceg), E. J. Gumbel (g), M. Koenig (abce), M. G. Landisman (abcdefgh), W. T. Mcguinness (bc), E. Lynn Savage (abfgh), E. Weber (d)
Brooktondale--H. G. Booker (cd)
Buffalo--S. Chapman (cd), F. S. Freeman (c), E. J. Kolkmeyer (b), H. H. Larkin, Jr. (cb), A. C. McTigue (b), B. L. Wiggin (c)
Canton--R. O. Bloomer (fh), A. P. Crary (abdh)
Chappaqua--G. S. Fox (g)
Croton-on-Hudson--E. S. Simpson (g)
Deposit--W. L. Sheafer (gh)
Dobbs Ferry--G. N. Cox (g), J. Northrup (e)
Downsville--T. W. Fluhr (dgh)
East Aurora--D. A. Parsons (g)
East Greenbush--E. E. Dittbrenner (g)
Ellenville--G. R. Ayer (g)

Forest Hills--J. F. Lynch (cd)
Fort Schuyler--M. H. Degani (cdeg)
Garden City--M. L. Brashears, Jr. (fgh)
Glen Cove--J. Honig (c)
Hamilton--D. K. Berkey (d), J. G. Woodruff (b)
Hartsdale--O. Wilhelm (gh)
Hicksville--K. J. Hauser (c)
Huntington--A. H. Johnson (g)
Irvington on Hudson--G. Kelton (bc)
Ithaca--A. L. Anderson (cfh), P. P. Bijlaard (fh), N. A. Christensen (abcdefgh), C. W. Gartlein (d), H. M. Johnson (ceg), G. B. Lyon (cg), L. A. Maynard (ex officio), R. D. Miller (cg), E. H. Muller (cfg), C. M. Nevin (abdeh), G. C. Sprague (cd), P. H. Underwood (adegh)
Jackson Heights--J. F. Dracup (a), L. Landau (ceg), W. S. Newman (bfgh), S. Partridge (c)
Jamaica--L. Harmantas (ce), A. Nazarek (cd), L. T. Olson (c)
Jamestown--J. P. Bedford (fgh)
Levittown--H. G. Kaplan (c)
Long Island City--C. R. Burrows (cd)
Lynbrook--J. F. Hoffman (abcdefgh)
Malverne--B. Shupack (ce)
Mineola--H. L. Frauenthal (gh), N. J. Lusczynski (g), R. M. Sawyer (g), J. E. Upson (g)
Mount Kisco--G. Emmons (ce)
Mount Vernon--A. S. Toth (g), H. A. Wadell (eg)
New York--H. A. Ackerman (ah), A. Al-Hamdani (ceg), J. C. Armstrong (e), L. Baer (cdeg), J. J. Baffa (g), A. F. Banfield (dg), G. F. Barnwell (abde), C. H. Behre, Jr. (fh), L. L. Behrendt (c), A. Beiser (cde), E. S. Belote (a), L. V. Berkner (cd), A. M. Bernstein (d), H. H. Beverage (d), M. A. Biot (bh), H. W. Bloomer (d), W. H. Bucher (ah), M. E. Burgunker (abcdefgh), P. H. Butticaz (bh), H. B. Churchill (b), M. E. Compton (abcd), R. G. Coulter (g), B. Davidson (ce), W. F. Davidson (cd), V. P. de Smitt (abceh), S. L. Dick (befh), L. H. Dicke (cg), G. G. Dixon , W. E. Dobbins (g), W. W. Doxey, Jr. (a), R. T. Duquet (ceg), J. L. Edwards (h), N. Efremov (df), B. F. Ellis (be), R. W. Fairbridge (eh), W. B. Farrington (aefgh), N. V. Feodoroff (g), W. O. Field, Jr. (g), J. E. Fisher (abeg), D. M. Gates (abcdefgh), J. J. Geraghty (g), J. B. Graham, G. R. Hamilton (abdeh), W. W. Hardy (abd), B. Haurwitz (cde), R. C. Haymes (d), Richard Hazen (cg), C. H. Helman, Jr. (c), V. F. Hess (cd), E. A. Hickok (bcfg), E. Holman (abd), L. H. Hutchinson (c), W. S. Jardetzky (h), W. Kaciak (cdeg), M. Kay (eh), P. F. Kerr (f), S. A. Korff (cd), E. M. Kovach (d), W. C. Lamb (bdh), D. W. Lea (ceg), Leggette, Brashears, and Graham (J. B. Graham, representative), R. W. Lenhard, Jr. (c), K. E. Lowe (fh), J. Lynch, S.J. (bh), B. H. Mason (efgh), G. H. Matthes (g), G. T. McCarthy (ceg), D. W. Miller (ag), E. V. Miller (cfg), J. E. Miller (c), M. M. Miller (g), R. D. Mitchell (g), R. D. Mollison (bdfh), T. V. Moore (be), H. R. Moorman (abd), I. M. Mostafa Elassiouty (g), F. W. Murray (c), R. Nebolsine (g), T. W. Nelson (abdgh), G. Neumann (e), W. S. Olson (abh), Parsons, Brinckerhoff, Hall, and Macdonald (G. G. Dixon, representative), W. J. Pierson, Jr. (ce), M. Pirnie (cg), A. Poldervaart (f), F. H. Pough (f), E. F. Preece (cg), F. L. Rhodes (acdg), E. G. Robles, Jr. (cdefg), R. J. Rommer (c), E. W. Rowland (g), P. C. Rutledge (g), T. Saville (ceg), S. Schaffel (fh), B. Schilit (c), R. F. Scott (abdef), O. A. Seager (abd), S. Sen (efh), Shell Oil Co. (F. Goldstone, representative), W. H. Sherman (aeg), K. E. Snelson (cg), R. G. Snider (ceg), J. Spar (c), E. W. Spencer (bgh), R. G. Stewart (g), A. N. Strahler (g), L. A. Stuebinger (cg), A.-G. Sultan (c), B. A. Tator (cd), M. H. Taylor (eg), C. Thor (c), L. R. Tucker (bc), A. Van Burkalow (cg), R. C. Vorhis (bg), L. G. Weeks (abcdefgh), W. S. Weyant (c), J. C. Whitaker (h), E. I. Williams, Jr. (e), W. A. Wood (acg)
Olean--W. J. Yahn (h)
Palisades--W. U. Ault (f), W. C. Beckmann (abdefgh), C. R. Bentley (abdefh), P. E. Damon (bdh), M. J. Davidson (abdf), C. L. Drake (abde), D. B. Ericson (e), M. Ewing (abcdeh), B. C. Heezen (abdefh), J. Hirshman (abde), J. L. Kulp (e), B. Luskin (abcde), J. E. Nafe (abde), J. E. Oliver (bce), P. W. Pomeroy (abdfh), B. M. Sarda (b), G. H. Sutton (abcdefgh), M. Talwani (abdeh), J. L. Worzel (abde)
Peekskill--G. M. Carhart (f), J. W. Irish (ag)
Piermont--J. F. Hennion (abef), G. B. Tirey (abde)
Pittsford--H. L. Alling (f)
Poughkeepsie--S. A. Schmitt (abcdefgh)
Port Jefferson--S. B. Cross (e)
Rhinecliff--G. A. O'Donnell (d)
Richmond Hill--W. Fedukowicz (e)
Riverhead--S. Goldman (d)
Rochester--H. S. Coleman (c), C.-S. Shu (acdg), J. M. Williams (cg)
Rocky Point--W. A. Miller (cd)
Saratoga Springs--L. W. Strock (ef)
Scarsdale--M. W. Garretson (fgh)
Schenectady--H. W. Ballew (bdh), R. Eisenstadt (g), A. R. Hersh, Jr. (a), I. Langmuir (ceg), K. A. Pauly (a), V. J. Schaefer (cg), E. S. C. Smith (bfg)
Scotia--H. Von Schelling (cg)
Stewart Air Force Base--W. E. Knight (c)
Syracuse--E. T. Apfel (cgh), N. E. Chute (efh), G. B. Cressey (cefg), P. E. James (c), W. S. Palius (bg), H. G. Wilm (cg)
Tarrytown--H. I. Brundage (begh)
Troy--R. F. Beers (abdefh), M. Dwonczyk (bde), L. C. Higbee (ag), E. J. Kilcawley (g), R. G. LaFleur (aceg), P. Lieber (bch), S. W. Lowman (abefh), H. N. Opland (bg), J. L. Rosenholtz (abdfh)
Tuckahoe--H. A. Miranda, Jr. (d)
Upton--O. A. Schaeffer (f), I. A. Singer (bcdeg)
Valhalla--F. J. Socey, Jr. (c)
Watervliet--D. T. Smith (bh)
Webster--H. J. Schutt (c)
West Albany--H. J. Smith (c)
Westbury--N. F. Lacey (c)
West Hempstead--A. L. Brown (ae)
White Plains--J. C. Harding (g), H. H. Helm (g), G. F. Kaufmann (abdh)
Whitestone--N. M. Perlmutter (ag)

North Carolina

Asheville--H. L. Crutcher (cg), A. B. Goodwin (g), C. R. Hursh (g), H. G. Meginnis (g)
Chapel Hill--R. W. Batten (ef), O. B. Eckhoff (bh), D. K. Hamilton (g), R. L. Ingram (eg), G. R. MacCarthy (bdfgh), V. I. Mann (a), C. M. Weiss (eg)
Charlotte--J. M. Howe (ceg)
Concord--V. A. Means, Jr. (g)
Durham--E. W. Berry (acefg), S. D. Heron, Jr. (f)
Morgantown--W. N. White (g)
Nags Head--F. B. Dinwiddie (ceh)
Raleigh--A. V. Hardy (c), D. G. Harris (c), H. G. Hinson (g), H. E. LeGrand (abdg), J. F. Lutz (g), E. L. Miller, Jr. (abcdefgh), E. B. Rice (cg), C. H. M. Van Bavel (g), J. Van Schilfgaarde (cg)
Waynesville--M. J. Gilbert (cg)
Winston-Salem--C. J. Champion, Jr. (cg)

North Dakota

Bismarck--H. C. McCreery (g), J. B. Shjeflo (g)
Grand Forks--J. R. Bergstrom (abcdefgh)
Riverdale--L. E. Curtis (c), R. V. Oehler (g), F. S. Witzigman (g)

Ohio

Athens--W. H. Carmean (g)
Bowling Green--J. R. Coash (beh)
Cincinnati--T. W. Bendixen (cg), B. R. Gilcrest (g), W. F. Jenks (fh), J. P. Lodge, Jr. (c), D. O. Martin (c), C. M. Relyea (c), R. C. Wanta (cde)
Cleveland--H. F. Birkenhauer, S.J. (bc), H. F. Donner (acf), A. C. Fograscher (eg), E. J. Walter (bc)
Columbus--R. J. Anderson (de), E. G. Barron (g), A. d'Audiffret (cg), R. K. Dodson (g), G. D. Dove (g), F. J. Doyle (a), A. H. Frazier (ag), J. Goodman (efgh), G. D. Harding (a), W. A. Heiskanen (abcdefgh), O. H. Jeffers (cg), E. A. Johnson (ag), F. H. Klaer (g), R. A. Krieger (g), T. Krumm (g), L. B. Laird (g), C. A. Lamey (defgh), S. H. Laurila (ac), W. C. Mahoney (a), F. C. Mikels (g), P. M. Pepper (acd), L. T. Pierce (c), H. J. Pincus (eh), R. W. Powell (g), Ranney Method Water Supplies (F. H. Klaer, Jr., representative), E. J. Schaefer (g), J. B. Schreiter (a), G. O. Schwab (cg), C. B. Sclar (abefh), G. R. Smith (cg), R. C. Smith (egh), W. L. Smith (defh), E. M. Spieker (gh), U. A. K. Uotila (abd), E. Van Cleef (cdh), W. C. Walton (g), E. E. Webber (g), G. W. Whetstone (g), C. V. Youngquist (g)
Coshocton--D. L. Brakensiek (g), F. R. Dreibelbis (g), L. L. Harrold (g)
Dayton--C. C. Chambers (g), G. J. Miatech (d), H. A. Miley (cd), C. C. Moeller (cg)
Delaware--N. T. Bobrovnikoff (a), W. P. Cross (cg)
Findley--P. M. Konkel, W. J. Yost (bd)
Granville--C. E. Graham (bh)
Grove City--S. E. Norris (g)
Hilliards--C. L. Hahn (g), W. H. Lewellen (g)
Marietta--G. H. Hayfield (efg)
Mount Vernon--O. S. Adams (a)
Oxford--J. E. Bever (fh), W. D. Martin (efg)
Parma--H. D. Dyck (c)
Portsmouth--D. J. Brumley (g)
Sandusky--R. P. Hartley (eg), J. L. Verber (g)
Toledo--W. H. Miller (c)
Vandalia--D. J. Roe (g)
Warren--F. Branden (c)
Worthington--W. J. Schneider (g)

Oklahoma

Ardmore--V. F. Jennemann (bceh), J. H. Speer (bcegh)
Bartlesville--D. A. Butler (abcdefgh), W. B. Weeks (bh)
Broken Arrow--E. O. McCutchen (abdeh)
Duncan--F. Gouin (acg)
Enid--J. E. Wright (bcg)
Goodwell--H. H. Finnell (cg)
Norman--G. R. Grantham (cg), F. A. Melton (efgh), J. A. E. F. Norden (abdefh), M. C. Oakes (fh), J. D. Pope (bde), W. Schriever (bcd)
Oklahoma City--K. M. Barry (bd), B. W. Beebe (bch), J. Bemrose (ab), M. B. Berger (g), J. E. Bucher (bd), W. L. Duggan (fh), S. K. Jackson (cg), H. W. Kinnan (c), L. L. Laine (g), R. H. Mansfield (bdh), N. Neece, Jr. (h), J. A. Pruett (cg), C. B. Smith (b), G. M. Sowers (fh), R. R. Wheeler (abh)
Ponca City--J. M. Crawford (a), H. J. Holland (f)
Stillwater--W. O. Ree (g)
Tulsa--A. J. Barthelmes (b), R. B. Baum (b), N. J. Bentley-Llewellyn (abcdefgh), T. J. Bevan (abdfh), W. T. Born (b), A. B. Bryan (abd), C. V. Campbell (eh), Carter Oil Co. (R. N. Meinert, representative), C. O. Clark (g), C. Coffin (abcdgh), A. E. Coldwell (g), R. B. Cox (g), W. J. Cunningham (b), A. R. Denison (beg), P. A. Dickey (bdh), K. Dyk (bfh), J. D. Eisler (bd), A. W. Engle (abd), L. Y. Faust (b), R. E. Fearon (abd), J. L. Ferguson (bce), C. Ferris (abch), R. S. Finn (b), J. M. Forgotson, Jr. (h), G. M. Friedman (f), Geophysical Research Corp. (J. E. Owen, representative), R. L. Geyer (bh), A. Gilmour (abdh), E. J. Handley (abcdefgh), A. J. Hickerson (cg), W. R. Holway (g), P. R. Jones (cg), V. L. Jones (abdh), K. T. Kimball (abfh), A. J. Kochendorfer (abcde), J. A. Kornfeld (bdf), C. C. Lash (bde), A. I. Levorsen (abgh), R. D. Lynn (b), P. L. Lyons (abdh), M. W. Major (abde), T. A. Manhart (bd), S. T. Martner (abdfh), E. V. McCollum (abh), A. W. McCoy, III (bfh), A. L. McCuistion (b), R. W. Mossman (b), A. N. Murray (beh), C. W. Oliphant (abdh), J. E. Owen, Pan American Petroleum Corp. (D. Silverman, representative), C. R. Pelto (fgh), W. B. Perry (abdh), R. A. Pohly (abcdefgh), N. H. Ricker (abcdeh), J. J. Roark (b), B. F. Rummerfield (abdh), C. Rynikker (bdfh), J. B. Sangree, Jr. (abe), G. D. Schedler (bh), S. A. Scherbatskoy (bd), M. E. Schmidt (g), Seismograph Service Corp. (G. H. Westby, representative), D. Silverman (abcdh), G. L. Taylor (abdh), H. M. Thralls (b), S. Von Croy (bd), T. H. Voth (g), R. J. Watson (abcdfh), B. B. Weatherby (bh), R. A. Weingartner (abdf), G. H. Westby (bd), M. B. Widess (abcdefgh), J. R. Winnek (b), J. E. Woodburn (abcdefgh)

Oregon

Beaverton--I. D. Allison (cg), E. M. Flaxman (g), C. E Hildebrand (g)
Cannon Beach--G. H. Canfield (g)
Corvallis--T. C. Adams (ag), W. V. Burt (ce), D. D. Evans (abcdefgh), G. S. Koch, Jr. (h)
Eugene--C. T. Bressler (bcdefgh), D. L. Weiss (g)
Ione--K. J. Smouse (acg)
La Grande--J. M. Trappe (cg)
Oswego--K. D. Earls (g)
Pendleton--G. M. Lee (cf)
Portland--R. T. Beaumont (cg), N. Bethlahmy (eg), I. Bloch (g), P. B. Boyer (eg), S. G. Brown (eg), W. E. Bullard, Jr. (g), L. A. Dean (cg), E. R. de Luccia (bg), E. G. Dunford (g), E. S. Ellison (cg), H. W. Firman (bg), H. J. Fittinger (cg), W. T. Frost (g), Z. R. Harper (g), J. R. Heller (cg), P. L. Heslop (cg), R. L. Hobba (g), H. Hulsing (g), C. E. Jencks (cg), D. W. Kuehl (cg), E. B. Latham (a), N. H. Leupold (g), C. W. Mansfield (cg), M. H. McClain (cg), G. R. Meigs (g), C. E. Mohler (g), A. Moore (g), F. Natella (ae), R. P. Olsen (ag), H. M. Orem (cg), C. Pedersen (cg), G. E. Philipsen (g), K. N. Phillips (cg), A. J. Polos (g), R. W. Revell (g), D. M. Rockwood (cg), M. S. Sachs (g), V. P. Schermerhorn (cdg), J. C. Stevens (g), J. Summersett, Jr. (g), H. A. Swenson (g), M. E. Thoms (g), R. A. Work (g)
Salem--W. S. Bartholomew (g), R. C. Edgerton (g), W. P. Lowry (cg), J. R. Morgali (cg), P. H. Ortman (eg), J. E. Sceva (g)
The Dalles--S. C. Sargent (f), A. L. Sharp (g)

Pennsylvania

Allison Park--C. R. Joller (d), R. W. Schmitt (g)
Ambler--J. W. Mauchly (cd)
Avoca--R. E. Simmermacher (cg)
Bala Cynwyd--A. W. Friend (cd), J. D. Hardy (c)
Bethlehem--A. H. Fretz (ef), H. R. Gault (fh), G. R. Jenkins (ceg), B. Willard (bcefgh)
Bradford--E. T. Heck (abdegh)
Bryn Mawr--E. H. Watson (abfh)
Canonsburg--E. L. Sulkowski (bc)
Carnegie--S. L. Bear (cg)
Cheswick--B. B. Cox (cegh)
Conestoga--E. T. Schuleen (g)
Cooperstown--W. M. Small (ceh)
East Lansdowne--A. G. Hely (g)
Easton--J. L. Dyson (g)

Ebensburg--F. A. Bender (abcdefgh)
Elkins Park--H. Jensen (ad)
Harmarville--J. C. Duecker (bcd)
Harrisburg--E. J. Coffey, Jr. (c), R. E. DuBois (g), D. W. Greenman (g), S. Mack (cfg)
Hatboro--C. R. Hosler (c), A. M. Stoll (c)
Havertown--E. W. Gain (g)
Huntingdon Valley--E. F. Bangs (d)
Johnstown--D. G. Nitch (bc)
Kingston--I. C. Reigner (g)
Lafayette Hills--L. M. Seavy (g)
Lansdowne--L. B. Corwin (cg)
Levittown--E. C. Rhodehamel (bcdefgh)
Lewisburg--G. A. Irland (b)
Lock Haven--H. F. Parker (g)
Meadville--D. W. Groff (b)
Milford--W. V. Iorns (g), W. R. Scott (g)
New Kensington--F. Keller, Sr. (b)
Newtown--F. Keller, Jr. (abcdfh)
Norristown--H. M. Mikami (defh)
Oakmont--E. A. Eckhardt (abdh), H. D. Hedberg (abdeh), J. C. Ludwick, Jr. (eg), D. H. Smith (b)
Oil City--F. A. Johnson (a)
Palmerton--F. T. Heuring (ad), R. K. Waring (bd)
Philadelphia--W. B. Agocs (bd), C. I. Aslakson (abcde), J. S. Burlew (fh), N. C. Courtney (g), D. E. Donley (cg), E. E. Foster (cg), P. W. Jordan (a), J. G. Kelley (a), H. Korkes (abc), N. R. Laden (g), H. Meier (acd), G. Mondrillo (cg), B. F. Santianni (acd), H. J. Schleh (ae), A. W. Weeks (h), C. F. Wicker (g), J. T. C. Yen (gh)
Pittsburgh--T. Bardeen (bd), E. Beutner (cg), T. A. Elkins (abdh), C. R. Fettke (befgh), Z. Frankenberger-Danes (abd), L. W. Gardner (bh), W. B. Gealy (bfh), A. I. Gregersen (abh), Gulf Research and Development Co. and Gulf Oil Corp. (L. J. Peters, representative), W. E. Hanson (efg), S. Hammer (abdh), M. J. Hill (befh), F. T. Mavis (g), M. Muskat (bdg), A. Nadai (bcefh), T. J. O'Donnell (abdh), H. W. Patnode (gh), L. J. Peters, T. L. Reilly (cg), R. G. Reiser (a), O. F. Ritzmann (bdh), H. Rockwood (cg), R. E. Rogal (cg), F. D. Rossini (ex officio), T. E. Stelson (g), P. C. Wuenschel (ab), R. D. Wyckoff (bdg)
Sewickley--A. E. Allen (g)
Solebury--F. T. McClintock (cde)
Swarthmore--F. K. Davis, Jr. (c), W. B. Keighton (g)
University Park--A. K. Blackadar (ceg), L. F. Herzog, II (abdh), C. L. Hosler (c), R. H. Howe (g), B. F. Howell, Jr. (abcdh), H. H. Neuberger (bch), H. A. Panofsky (c), J. A. Ryan (bdh), S. Shulits (ceg), C. J. Smith (g), C. P. Thornton (h), R. J. Urick (be), A. H. Waynick (d), B. A. Whisler (g), D. O. Wyble (abeh)
Upper Darby--G. R. Hall (g), H. W. Lull (g), F. H. Olmsted (fg), G. G. Parker (cefg)
Villanova--F. H. Larson (g)
Wallingford--C. B. Bazzoni (bcdeh)

Puerto Rico

Mayaguez--J. D. Weaver (dh)
Rio Piedras--D. C. McDowell (c)
Roosevelt--A. D. Sollins (a)

Rhode Island

Kingston--F. T. Dietz (be)
Providence--W. B. Allen (g), C. W. Brown (bcfh), C. Freeman (bf), A. W. Quinn (abfgh)
Warwick--A. C. Chick (bcg)
Woonsocket--N. J. Oliver (d)

South Carolina

Aiken--C. W. Thorngate (ceg)
Charleston--W. Candrick (cg), J. A. Cummings (ce)
Clemson--D. D. Curtis (cg), T. V. Wilson (g)
Columbia--W. W. Evett (g), A. E. Johnson (g), G. E. Siple (abefg), S. Taber (bcefgh), F. W. Wagener (g)
Greenville--E. W. G. Kliemann (c)
Pickens--T. J. Mitchell (ace)
Spartanburg--E. F. Carmichael (g), J. W. Roehl (g)

South Dakota

Brookings--L. O. Fine (g), M. M. Fogel (cg)
Buffalo--G. H. Farrance (bd)
Huron--R. H. Corcoran (g), A. F. Geiger (g), W. T. Hodge (cg), C. V. Pierce (abefgh), W. H. Wells (c)
Rapid City--E. L. Tullis (bdgh)
Vermillion--R. E. Stevenson (bf)

Tennessee

Chattanooga--W. R. Eaton (g), J. W. Gambrell (g), N.H. Williams (cg)
Elizabethton--E. S. Daly (g)
Erwin--C. E. Hunter (bf)
Johnson City--R. L. Parson (aceg)
Knoxville--C. T. Barker (bg), A. Blickensderfer (cg), W. A. Bowmaster (cg), B. W. Brown, Jr. (cg), B. J. Buehler (cg), A. J. Cooper (cg), A. S. Fry (cg), B. C. Moneymaker (bg), D. W. Newton (cg), J. T. Price (aceg), M. M. Richards (cg), E. J. Rutter (g), R. E. Shanks (cg), J. Smallshaw (cg), W. M. Snyder (cg), J. H. Wilkinson (g)
Limestone--W. K. Mahoney (c)
Memphis--W. H. Banks (cf), E. M. Cushing (g), A. L. King (cg), G. T. Stephens (c), S. I. Strausberg (gh), P.-C. P. Sun (aceg)
Nashville--H. J. Blazek (g), W. C. McNeill (cg), J. T. Mitchell, Jr. (g), A. G. Schafer (g), R. G. Stearns (h), C. W. Wilson, Jr. (a)
Norris--R. A. Elder (g)
Oak Ridge--W. de Laguna (g)
Sewanee--E. McCrady (bfh)
Signal Mountain--I. J. Hickenlooper (g), C. Wells (g)

Texas

Abilene--R. Miller (acefgh)
Alpine--K. J. DeCook (g), C. E. Gray (bfh)
Amarillo--R. C. Barber (bcdfh), A. C. Hornady (a), E. L. Pemberton (g)
Arlington--M. Pollard (fh)
Austin--R. B. Anders (cefg), T. Arnow (g), R. C. Baker (g), V. E. Barnes (aefh), H. R. Bentley (cg), S. D. Breeding (g), F. M. Bullard (ef), H. P. Bybee (ah), S. E. Clabaugh (fh), W. E. Clark (g), G. G. Commons (cg), R. K. DeFord (g), W. W. Doyel (g), D. H. Eargle (g), P. T. Flawn (fh), W. O. George (g), J. R. Gerhardt (ce), W. H. Goines (g), W. F. Guyton (g), C. W. Horton (abh), D. S. Hughes (abeh), H. W. Ireton (cg), M. L. Klug (g), L. J. B. LaCoste (ab), A. T. Long (bfgh), J. T. Lonsdale (fgh), R. L. Lowry (cg), W. L. Moore (eg), C. W. Morgan (acg), E. A. Moulder (g), W. R. Muehlberger (efgh), J. H. Nienaber (efgh), J. W. Pritchett (acg), C. B. Reed (b), R. W. Rush (e), M. G. Schwab (g), R. C. Staley (c), I. M. Stout (abcdgh), R. W. Sundstrom (g), T. Twichell (g), A.G. Winslow (ag), K. Young (ah)
Baird--C. P. Porter (abcdefgh)
Bay City--A. H. Wadsworth, Jr. (bdfgh)
Beaumont--S. Aronow (g), F. R. Beck (abcdefgh), T. R. Cheesman (ab), J. W. Millington (abd), B. E. Richert (d), J. E. Steele (e)
Bellaire--L. E. Borgman (e), W. Eckley (abdeh), B. D. Lee (b), P. H. Masson (fh), J. R. Moore, III (eh), H. Ode (h), J. W. Phillips (abd), G. W. Postma (bdh), J. H. Rosenbaum (bef), D. C. Van Siclen (ah), J. H. Veasaw (bdgh)

Brownsville--S. S. Nye (g)
Bryan--G. A. Franceschini (ce), R. D. Tarble (cg)
Cisco--R. E. Lee (abdfh)
College Station--R. M. Adams (ce), R. G. Bader (e), H. R. Blank (g), J. D. Cochrane (e), P. Dehlinger (abch), K. H. Drummond (e), R. D. Gaul (ce), R. A. Gilcrest (ce), M. H. Halstead (c), D. W. Hood (de), A. M. Kahan (cg), D. F. Leipper (ce), M. G. H. Ligda (c), H. J. McLellan (e), R. O. Reid (ce), W. J. Saucier (c), B. W. Wilson (ceg)
Corpus Christi--L. B. Clarkson (e), E. A. Lohse (abcdefgh), W. F. Pfennig (b), W. A. Price (ceg), F. R. White (abcdefgh)
Crystal City--J. W. Flanagan (g)
Dallas--D. O. Acrey (bh), C. C. Albritton, Jr. (bfgh), K. Arnold (abcdefgh), M. M. Backus (abdefh), W. C. Bednar, M. Bigger, Jr. (b), J. S. Bradley (eh), D. F. Brennan (bdfh), H. H. Brown (b), K. E. Burg (abdh), D. H. Clewell (bdeh), H. L. Cobb (a), H. C. Cortes (b), J. W. Davis (acg), T. E. Dennis (b), J. C. Dunlap (eg), H. W. Feldt (acg), F. K. Fisk (abcdgh), I. S. Fuqua (aefh), Geotechnical Corp. (R. F. Beers, representative), C. H. Green (b), I. H. Hale (cg), A. H. Halff (g), J. W. Harrington (dh), W. B. Heroy (abfg), W. B. Heroy, Jr. (abdh), J. H. Hoke (bef), W. L. Horner (g), J. J. Idema (g), F. T. Johnston (h), M. P. Jones (ab), L. W. MacNaughton (eg), Magnolia Petroleum Co. (H. C. Cortes, representative), R. Mayer, Jr. (bd), M. D. McCarty (bde), E. McDermott (bdfh), E. W. McLemore (bg), D. A. McNaughton (g), W. G. Meyer (bh), Meyer and Achtschin (W. C. Bednar, representative), C. G. Morgan (bef), P. E.Nash (abcdefgh), E. B. Neitzel (bd), W. W. Newton (b), V. E. Oppenheim (efh), H. B. Peacock (abdh), W. R. Ransone (abcfg), D. Renner (b), R. E. Rettger (abh), E. D. Riggs (b), J. F. Rollins (b), W. B. Roper (a), E. E. Rosaire (abdfgh), H. W. Rose (abdh), E. R. Scott (bcdgh), W. E. Sell (abd), G. F. Shepherd (bd), W. B. Sherman (cd), R. A. Stehr (abh), F. O. Swiggart (ceg), Texas Instruments, Inc. (J. A. F. Gerrard, representative), R. M. Tripp (bdh), E. G. Trostel (abdh), G. Vorbe (bgh), H. F. Williams (e), H. F. Wise (bh), J. P. Woods (b)
Dumas--W. H. Alexander, Jr. (cg)
El Paso--J. F. Friedkin (g), E. E. Hamlyn (a), L. H. Henderson (fgh), T. E. Henderson (g), W. F. Resch (g), G. W. Smith, Jr. (acg), W. L. Webb (cdg)
Fort Sam Houston--W. R. McCutchen (h)
Fort Worth--R. G. Andrews (g), F. L. Aurin (b), R. W. Baird (cg), W. D. Baird (ab), W. R. Berger (bgh), E. L. Burnett (g), J. Divelbiss (bd), D. Donoghue (g), D. G. Egan (bcdgh), S. W. Freese (cg), P. S. Groginski (abcdefgh), E. L. Hardy (cg), S. Harris (b), C. J. C. Harvey (bgh), K. C. Heald (bd), L. Hendricks (fh), H. E. Itten (b), E. A. Krieg, Jr. (bde), R. H. Lang (b), P. H. Ledyard (b), R. J. MacConnell (cg), H. Matson (g), C. Miron (g), J. D. Moody (befh), J. Morgan (d), C. E. Roberts (g), R. H. Schweers (cdefgh), K. V. Speeg (cg), G. L. Walder (cdeg), R. H. Wesley (begh), J. H. Wilson (abdh), W. E. Wood (cg)
Galveston--E. H. Brown (g)
Garland--H. S. Aurand, Jr. (abcdefgh)
Houston--J. L. Adler (abdfh), A. F. Amante (bh), L. T. Barrow (abeg), O. G. Bell (abce), M. L. Benke (b), J. L. Bible (abdh), B. P. Bishop (d), J. P. Black (b), L. W. Blau (bdh), R. Blumberg (bcdeg), M. A. Bohannan (b), T. W. Bonner (d), O. L. Brace (bc), S. H. Buckley, S. E. Buckley (g), J. E. Buescher, J. Bush (e), D. P. Carlton (abdeh), M. F. Carman, Jr. (abdfh), K. Carter (b), S. R. Casey, Jr. (h), C. J. Charske, Jr. (b), E. L. Clifford (b), D. G. Coppedge (bcd), J. R. Cornett (b), H. P. Coster (b), I. H. Cram (abh), C. Croneis (cegh), M. J. Davis (bdh), D. A. DeWoody (b), M. A. Dillingham (g), J. H. Dunaway (bc), C. H. Fay, H. N. Fisk (gh), J. C. Freeman, Jr. (ce), A. Frosch (bd), V. G. Gabriel (abdefh), D. H. Gardner (bh), J. A. F. Gerrard (bdh), R. E. Gilliland (bdh), F. Goldstone (abdh), H. R. Gould (efg), A. B. Hamil (b), J. W. Handin (abefgh), M. A. Hanna (eg), N. C. Harding, T. I. Harkins (b), G. H. Harrington, Jr. (abdefh), J. T. Hartman (abdh), D. V. Higgs (fh), R. C. Hilton (bdh), L. Horvitz (abd), Houston Technical Laboratories (N. C. Harding, representative), L. G. Howell (abd), F. W. Howells (beh), K. J. Hsu (fh), C.-W. Huang (g), M. K. Hubbert (abdegh), J. S. Ivy (b), R. M. Jeffords (g), H. J. Jones (bh), S. A. Judson (dh), F. M. Kannenstine (b), G. E. Kramer, Jr. (b), R. O. LaRue (b), E. G. Leonardon (bdfgh), L. B. Lipson (abdh), G. M. Mace, Jr. (b), M. R. MacPhail (abdh), W. M. Malicoat (abd), W. H. Mannes (bdg), J. D. Martinez (abdgh), K. G. McCann (b), B. McCollum (bd), E. T. Miller (bd), C. L. Moody (bdfh), L. M. Mott-Smith (ad), P. H. Nelson (e), L. L. Nettleton (abdh), C. B. Officer (abe), R. W. Olson (bd), C. C. Palmer (bcd), G. R. Pickett (b), B. O. Prescott (bg), C. M. Quigley, Jr. (eg), J. R. Randolph (bh), R. H. Ray (ab), V. L. Redding (bch), J. A. Rickard (efgh), M. J. Rieger (abdh), W. L. Roever (bd), J. J. W. Rogers (f), F. W. Rolshausen (egh), F. E. Romberg (bh), R. A. Rowland (abgh), W. E. A. Ruska (d), Ruska Instrument Corp. (S. H. Buckley, representative), W. M. Rust, Jr. (abd), R. L. Sargent (ab), R. R. Sartain (e), J. H. Sasseen (bdh), J. R.Schander (bdh), H. Schmidt (b), J. P. Schumacher (abdh), H. A. Sears (b), B. J. Shearer (ce), Shell Development Co. (C. H. Fay, representative), E. J. Shimek (bcde), S. E. Sims (ab), N. J. Smith (abdeh), N. D. Smith, Jr. (b), G. B. Somers (bcdh), C. D. Speed, Jr. (abdfh), T. B. Stanley, Jr. (ag), E. Statham (d), N. C. Steenland (dh), E. F. Stratton (bfh), E. Strick (be), R. C. Sweet (abc), E. F. Taylor (aeh), J. Taylor (b), R. E. Taylor (adeg), R. R. Thompson (bd), A. B. Tinsley (abh), M. P. Tixier (bd), Vector Manufacturing Co. (J. E. Buescher, representative), C. B. Vogel (bd), H. C. Warren (b), P. Weaver (bdfgh), M. M. Welch (abe), E. A. Wendlandt (abh), J. E. Werner (bedfh), E. D. Williams (b), M. Williams (aefh), A. Wolf (bdh), C. S. Wolston (ab), L. A. Wood (g), R. D. Woods (agh), S. P. Worden (a), C. C. Zimmerman (abdh), N. N. Zirkel (bdh)
Irving--J. H. Halsey (fh)
Kingsville--J. H. Cross (bdfh)
Laredo--K. F. Keeler (cg), J. B. Ringwood (g)
Lockhart--F. W. Wiegand (abd)
Lubbock--W. L. Broadhurst (g), A. M. Di Renzo (bdh), H. Klaus (abdh), F. A. Wade (fgh), G. W. Willis (cg)
Mercedes--W. D. Parish (cg)
Midland--J. E. Adams (egh), J. W. Daly (bd), G. R. Gibson (h), B. R. Haigh (a), W. E. Hall (abcefh), C. C. Miller (b), R. D. Miller (bcdh), J. S. Pluta (abcdefh), J. I. Rael (abcdefgh), J. P. Rodgers (f), M. Spencer (de), B. A. Tuller (b), L. F. Uhrig (abcdh)
Nacogdoches--G. K. Stephenson (g)
New Braunfels--A. L. Wilkinson (b)
North Uvalde--F. A. Welder (eg)
Plainview--J. G. Cronin (abfg), W. V. Mickey (b)
Port Aransas--H. T. Odum (ce)
Port Arthur--J. D. Weldon (h)
San Angelo--V. J. LaForge (ab), J. I. Moore (b)
San Antonio--M. E. Arnold, Jr. (b), E. A. Brown (g), W. W. Carter, Jr. (b), J. C. Cook (bd), J. W. E. Edmonson (abdh), D. H. Gould (c), A. F. Hasbrook (abe), J. L. Howell (ceh), A. A. Jergins (bh), P. E. Narvarte (b), E. W. Owen (ef), J. O. Parr, Jr. (abdh), B. M. Petitt, Jr. (g), D. E. Petty (abdeh), O. S. Petty (abdh), D. H. Rowden (befgh), R. J. Scofield (abcdgh), H. A. Seran (a), J. T. Spann, Jr. (bcg), R. A. Thompson, Jr. (g)
Seguin--R. K. Blumberg (b)

Sherman--H. L. Schiflett (ad)
Sinton--R. D. White (gh)
Stonewall--T. W. Weinheimer (g)
Tyler--J. R. Bunn (h), J. S. Hudnall (abgh), G. J. Loetterle (beg)
Victoria--A. B. Elliott, Jr. (bcefg)
Waco--T. E. Darby (h), M. A. Hartman (g), G. L. Lanman (abcefg)
Whitesboro--M. T. Bentley (a)

Utah

Alta via Sandy--E. R. LaChapelle (g)
Bountiful--D. R. Mabey (abdh)
Farmington--R. B. Marston (g)
Logan--W. Gardner (gh), C. T. Hardy (bd), A. B. Harris (acg), D. W. Hendricks (g), O. W. Israelsen (g), W. N. Jibson (ag), C. W. Lauritzen (g), A. D. Smith (cg), S. A. Taylor (g), J. S. Williams (bgh)
Ogden--R. W. Bailey (g), G. W. Craddock (g), A. R. Croft (g), J. O. Reeve (g)
Orem--C. E. Jacob (abcdefgh)
Provo--K. F. Bickford (befgh), D. K. Fuhriman (g)
Richfield--R. A. Young (g)
St. George--R. V. Wyman (defgh)
Salt Lake City--T. C. Adams (abcg), W. E. Anderson (g), W. E. Bales (dfh), J. W. Berg, Jr. (bh), R. L. Cabell (g), F. W. Christiansen (bfh), K. L. Cook (bdh), A. J. Eardley (h), E. A. Elevatorski (g), H. B. Evans (abcd), A. E. Granger (f), D. Hager (h), J. V. Hales (cdeg), I. W. Marine (g), W. T. Nightingale (bdfh), R. T. Novotny (abcdefgh), J. W. Odell (g), E. L. Peck (cg), A. W. Pinger (dh), J. K. Reid (g), C. T. Snyder (g), W. P. Somers (g), S. W. Stewart (bd), W. L. Stokes (gh), A. O. Taylor (f), H. A. Waite (acgh), N. C. Williams (fh), C. H. Wilson (abd), M. T. Wilson (cg)
Sandy--W. L. O'Toole, Jr. (df)
Scofield--W. E. Zabriskie (bg)

Vermont

Burlington--E. C. Jacobs (bfh), J. A. Root (ag)
Essex Junction--C. G. Doll (h)
Montpelier--W. M. Cady (fh), A. H. Chidester (fh)
Northfield--L. M. Laushey (g)
Shelburne--H. N. Stapleton (cg)
South Londonderry--D. T. O'Connell (bcfh)

Virgin Islands

St. Thomas--D. Parson, Jr. (cde)

Virginia

Alexandria--J. K. Angell (c), J. E. Caskey, Jr. (ceg), H. L. Croom (c), G. L. Evans, Jr. (bfg), M. I. Goldman (eh), R. A. Hoover (c), W. M. Kaula (a), L. F. Kengle, Jr. (e), M. M. Kenney (a), J. A. Minogue (aceg), R. H. Nesbitt (abcdefgh), K. M. Sandals (cg), L. A. Smitherman (bd), D. J. Weigle (bdefh), J. E. Woolhiser (e)
Annandale--E. H. Bramhall (bcdh)
Arlington--H. W. Adams (cg), L. Alpert (ceg), O. J. Baldwin (cg), M. A. Benson (cg), S. H. Birdseye (a), F. L. Blue, Jr. (eg), M. E. Britton (abcdefgh), A. C. Campbell (a), E. C. T. Chao (abcdefgh), W. T. Collins (cg), H. V. Darling (g), J. J. Davis (c), D. R. Dawdy (g), H. Demboski (cg), J. A. De Pue (cd), E. G. Droessler (c), W. S. Eisenlohr, Jr. (g), E. G. Engle (c), W. R. Farley (g), G. E. Ferguson (g), J. R. Finton (ce), E. F. Ford (cg), R. G. Grassy (abcdefgh), D. R. Harris (c), H. B. Harshbarger (c), D. M. Hershfield (cg), R. A. Hertzler (g), B. L. Hobbs (g), F. W. Hough (ab), D. K. Jenkins (a), D. S. Jenkins (g), C. H. Jennings (cg), G. A. Kirkpatrick (g), H. W. Larsen (abdfgh), F. L. Meara (gh), C. P. Mook (c), J. H. Nelson (bd), C. T. Newton (g), H. O. Ogrosky (g), L. Pocinki (ce), J. K. Searcy (g), P. A. Siple (ch), P. A. Smith (ae), F. F. Snyder (cg), R. C. Vetter (e), R. O. Williamson (a), M. S. Wright, Sr. (abcdefgh)
Blacksburg--R. V. Dietrich (fh), C. E. Sears (abd)
Charlottesville--E. M. Miller (g), W. A. Nelson (bdeh), E. H. Ogilvie (g), A. Sinnott (fgh), R. H. Tice (g)
Churchville--A. Bevan (bgh)
Corbin--J. H. Baden (bcd), R. E. Gebhardt (bcd), T. L. Skillman (bd), J. B. Townshend (d)
Fairfax--W. H. Durum (g), W. B. Foster (ce), W. L. Mangler (g), V. A. Myers (c)
Falls Church--J. M. Beall (c), W. J. Best (bc), G. L. Bowie (cg), R. W. Carter (cg), W. H. Geddes (d), L. C. Gottschalk (bg), J. C. Hagan (ceg), L. A. Koffman (g), L. Lassen (g), R. J. List (c), L. Machta (c), N. A. Matson (c), R. E. Oltman (g), D. H. Pack (abcd), A. A. Poling, Jr. (a), L. O. Quam (cg), D. Richardson (cg), H. C. Riggs (g), C. F. S. Sharpe (cg), T. S. Southwick (cg), A. J. Steele (c), J. P. Webber (c), J. V. B. Wells (g), H. Wexler (c)
Fort Belvoir--W. C. Cude (a), G. H. Hickox (g)
Fort Monroe--H. B. Hutchinson (ce)
Hampton--V. M. Haywood (a)
Herndon--R. M. Harding (cg)
Lorton--P. Bartsch (eg)
Lucketts--W. J. Ware (g)
Lynchburg--H. V. Myers (c)
Manassas--S. Krasnow (abcdefgh)
Middleburg--D. H. Read (ac)
Mineral--R. B. Fulton, III (dh)
Mount Vernon--M. L. Phillips (cd)
Norfolk--A. L. Cherry (ae), H. J. Fine (cg), J. F. Tatom (ce)
Purcellville--L. G. Laure (a)
Richmond--M. E. Beatty (g), S. S. Schworm (cg), G. S. Sydnor, Jr. (g)
Sandston--F. L. Dix (bcd)
South Boston--W. E. Patten (g)
Springfield--D. L. Broyles (ah), A. H. Predzin (bd)
Sterling--R. W. Stallman (g)
Vienna--W. D. Romig (g), W. T. Stuart (g)

Washington

Bellevue--D. E. Blunt (g)
Bremerton--J. H. Fyten (adfg)
Ephrata--E. Nasburg (g)
Kitsap--J. T. Shaw (e)
Marshall--L. L. Oriard (bg)
Mercer Island--E. Colton (bcdeh)
Olympia--W. A. G. Bennett (fgh), R. H. Russell (g)
Pullman--C. L. Barker (cg), H. E. Culver (bcf), G. H. Dunstan (cg), I. L. Maytin (g), J. A. Roberson (g)
Richland--W. H. Bierschenk (g), D. J. Brown (afg), R. E. Brown (fh), J. J. Fuquay (c), A. T. Gifford (cg), M. W. McConiga (fg), J. R. McHenry (g), J. R. Raymond (g), P. P. Rowe (g)
Seattle--F. I. Badgley (c), C. A. Barnes (e), R. C. Becker (cdg), H. R. Blank, Jr. (dgh), E. B. Brown (ade), E. C. Brundage (g), K. Buettner (cdg), T. H. Campbell (g), R. J. Chang (cg), P. E. Church (ceg), H. A. Downs (ceg), A. Ehrlich (c), R. G. Fleagle (ce), R. H. Fleming (e), R. E. Fuller (f), J. A. Gast (e), S. P. Gessel (fg), P. A. Goldberg (d), G. E. Goodspeed (bf), R. A. Hall (abdh), A. E. Harrison (g), G. W. Holmes (g), R. W. Jones (g), J. H. Lincoln (e), E. H. Linger (ceg), J. H. Mackin (g), M. D. Magnuson (c), D. R. Makela (cg), P. M. McLellan (eg), P. Misch (bh), F. Neumann (abd), R. G. Paquette (e), M. Rattray, Jr. (e), L. A. Sanderman (efh), P. E. Seelinger (eg), R. A. Skrinde (cg), N. L. Stoltenberg (g), T. G.

Thompson (ceg), M. A. Wolf (abcdg)
Spokane--R. O. Cox (c), C. S. Hazen (g), E. C. Stephens (fh), D. B. Wiebe (ceg)
Tacoma--D. G. Anderson (g), E. G. Bailey (g), G. L. Bodhaine (g), D. F. Calkins (g), B. L. Foxworthy (g), W. C. Griffin (cg), H. A. Hagestad (g), F. A. Johnson (cg), F. F. Lawrence (g), A. V. Leppanen (g), M. F. Meier (cegh), E. G. Pearson (g), F. B. Roberts (cg), J. A. Roller (g), W. D. Simons (cg), F. M. Veatch (g)
Vancouver--D. J. Bauman (cg), L. M. Bissell (c), D. H. Hart (g), R. L. Washburn (g)
Walla Walla--M. J. Ord (cg)

West Virginia

Bluefield--R. M. Allen, Jr. (g)
Huntington--G. F. Connell (g)
Keyser--C. B. Yost, Jr. (dfgh)
Morgantown--C. W. Carlston (g), R. C. Colwell (c), P. H. Price (bc)
Parsons--K. G. Reinhart (g)
Princeton--H. W. Straley, III (abcdefgh)

Wisconsin

Appleton--A. C. Braun (cg), C. A. Joyce (abdh), J. C. Kurtyka (cg), L. W. Weis (abcdefgh)
Beloit--J. D. Swannack (abg), H. H. Woodard, Jr. (fh)
Chippewa Falls--N. A. Ostenso (abe)
Madison--R. F. Black (gh), R. H. Brigham (g), W. J. Drescher (g), R. C. Emmons (adfh), N. N. Gunaji (cg), R. A. Haubrick, C. L. R. Holt, Jr. (gh), H. J. Hunt (g), K. Koenen (abdh), A. T. Lenz (cg), E. F. Le Roux (cg), J. W. Mack, Jr. (abd), N. E. Minshall (g), J. C. Rose (ab), C. R. Stearns (ce), J. Steinhart (abd), V. E. Suomi (cg), C. B.Tanner (gh), G. P. Woollard (abd)
Milwaukee--W. J. Abrams (g), E. F. Dosch (g), S. Karrer (abcdefgh), E. E. Rexin (bdfg), A. R. Striegl (g), H. J. Thompson (cg)
Stevens Point--J. C. Behrendt (abd)
Tomahawk--E. H. Martin (c)
Tony--W. A. Sybers (g)
Wausau--E. Thiel (abdeh)
Williams Bay--J. W. Chamberlin (d), G. P. Kuiper (abcdh)

Wyoming

Casper--R. W. Craig (b), W. H. Fenwick (abdh), R. B. McConnell (aceh), R. L. Streeter (g)
Cheyenne--H. M. Babcock (g), P. A. Rechard (acg)
Cody--G. S. Buchanan (efh)
Green River--G. T. L. Wongwai (f)
Laramie--D. L. Blackstone, Jr. (bh), R. C. Shopland (b), J. H. Zoller (g)
Riverton--W. B. Peters (g)
Rock Springs--J. D. Honerkamp (g)
Worland--T. F. Hanly (g), W. L. Haushild (g), G. L. Higgins, Jr. (bg)

FOREIGN COUNTRIES

Canada (by post offices)

Algoma Mills, Ontario--R. J. Cook (adefh)
Antigonish, Nova Scotia--D. J. MacNeil (e)
Bathurst, New Brunswick--P. R. Heenan (abfgh)
Calgary, Alberta--C. H. Acheson (bd), W. F. Albers (b), M. Aydin (b), A. W. Bally (efgh), E. W. Beltz (bcdegh), W. E. Blakely (abh), D. B. Bullock (fh), C. L. Cain (bd), H. L. Cameron (aefh), R. L. Carter (cg), C. E. Chesher (b), G. L. Cumming (bfh), R. E. Davis (abdh), M. B. Dobrin (bdh), H. L. Farney (b), E. L. Fetzer (b), G. G. Gibson (b), P. E. Gretener (bdefgh), W. C. Gussow (h), J. D. Hale (bdh), W. R. Hanson (cg), G. R. Hess (beh), W. C. Howells (abfh), R. C. Hyslop (bcdh), A. Junger (bfh), W. A. Knox (a), T. A. Link (h), H. C. Maliphant (abdh), I. C. Mayfield, Jr. (b), H. R. McCormack, Jr. (h), M. H. McKinsey (ab), V. C. Miller (g), T. W. Morrison (abcdefgh), W. H. Myers (bdc), A. E. Pallister (abde), A. R. Patterson (b), H. Pearson (abdefh), W. G. Rimmer (abdefh), R. B. Ross (b), D. M. Sargent (b), J. C. Scott (b), D. C. Skeels (abdefh), D. W. Smith (bdefh), J. A. Smith (bdfg), R. C. Smith (ab), W. F. Stackler (abdh), H. H. Suter (befh), A. G. Underhill (g), E. F. K. Zarudzki (bh)
Chalk River, Ontario--D. A. Keys (abd)
Cumberland, British Columbia--A. F. Buckham (h)
Dawson Creek, British Columbia--G. H. Weisser (b)
Dobie, Ontario--D. W. Tully (f)
Don Mills, Ontario--F. T. Clifton (abdh), W. O. J. Groeneveld Meijer (abdfh), K. Vozoff (abdfh)
Edmonton, Alberta--G. D. Garland (abdh), W. P. Ogilvie (bh)
Elliot Lake, Ontario--R. C. Heim (fh)
Esquimalt, British Columbia--W. L. Ford (e)
Guelph, Ontario--F. R. Hore (g), R. W. Irwin (g)
Haileybury, Ontario--E. L. MacVeigh (h)
Halifax, Nova Scotia--H. S. Heaps (eh), J. R. Longard (e)
Hamilton--H. S. Armstrong (efgh)
Kingston, Ontario--E. E. Watson (e)
Lethbridge, Alberta--K. C. Thomson (b)
London, Ontario--A. Dreimanis (fgh)
Manotick, Ontario--L. W. Morley (abcdh)
Maple, Ontario--D. V. Anderson (beg)
Montreal, Quebec--A. D. Belmont (cg), R. Boucher (g), L. Cartier (cg), H. M. Finlayson (g), J. W. Forster (cg), P. G. Gauthier (ab), J. E. Gill (h), H. Kaufman (bd), D. McIntyre (cg), J. C. Morgan (g), K. Mullerbeck (ag), V. Saull (bf)
Nanaimo, British Columbia--S. Tabata (ce), J. P. Tully (ce), M. Waldichuk (e)
Noranda, Quebec--P. Price (abdfh)
Onaping via Sudbury, Ontario--A. D. Mutch (abcdfgh)
Ottawa, Ontario--W. D. Baines (g), C. S. Beals (a), W. M. Cameron (ce), R. H. Clark (g), L. S. Collett (fh), L. A. Gale (a), M. J. S. Innes (abdh), J. E. Lilly (a), J. D. McLeod (cg), M. S. Reford (abdh), J. E. R. Ross (a), A. E. Scheidegger (gh)
Peace River, Alberta--W. D. Black (bh)
Quebec, Quebec--R. J. M. Miller (dfh), A. D. Misener (dh), R. W. Packer (ceg), E. G. Pleva (cg), R. J. Uffen (dfh), G. O. Villeneuve (ceg)
Regina, Saskatchewan--W. M. Berry (g), W. R. M. Williamson (b),
St. Andrews, British Columbia--N. J. Campbell (e), H. B. Hachey (e)
St. James, Manitoba--W. W. Ramsay (g)
Saskatoon, Saskatchewan--A. R. Byers (h), B. W. Currie (cd)
Swastika, Ontario--J. W. McBean (bdf)
Timmins, Ontario--W. A. Jones (dfh)
Toronto, Ontario--A. A. Arajs (g), R. S. Arden (g), J. B. Boniwell (bdfg), R. A. Bosschart (bdfh), R. R. Brooks (b), R. E. Deane (efh), R. M. Farquhar (dfh), L. Gilchrist (acd), R. L. Hearn (cdg), C. C. Huston (dh), J. A. Jacobs (df), G. R. Johnson (adh), N. B. Keevil (bdfg), G. B. Langford (fgh), H. T. Lundberg (adh), P.-S. Quan (g), R. D. Russell (dfh), D. J. Salt (d), H. O. Seigel (abdg), E. G. Tallman (g), S. H. Ward (d), E. W. Westrick (bcd), J. T. Wilson (h), H. A. Winkler (b)
Trail, British Columbia--C. O. Swanson (def)
Truro, Nova Scotia--J. E. Blanchard (bd)
Val d'Or, Quebec--T. Koulomzine (d)
Vancouver, British Columbia--L. Adler (ad), A. R. Clark (abd), G. J. A. Kidd (acg), W. H. Mathews (fg), G. L. Pickard (eg), H. T. Ramsden (g), V. Raudsepp (g), A. Smith (abcdefgh), C. E. Webb (cg)

Virginiatown, Ontario--J. W. Baker (df)
West Calgary, Alberta--W. H. Hohag, Jr. (b)
Westmount, Quebec--H. R. Kivisild (bceg)
Willowdale, Ontario--R. G. Hoiles (fgh), O. Holden (g), W. G. Wahl (d)
Winnipeg, Manitoba--N. Mudry (cg)
Wolfville, Nova Scotia--R. H. Magarvey (ce)

OTHER FOREIGN COUNTRIES
(by countries)

Algeria--G. Grenet (bd)
Argentina--L. R. A. Capurro (e), H. Etchebehere (e), J. C. Gurmendi (b), G. J. Heinsheimer (g), J. Jagsich (ace), R. Martin (abdeh), R. N. Panzarini (e), O. Schneider (abcdefgh), G. Schulz (abcdh), L. Slaucitajs (deg), J. J. Zunino (abdh)
Angola--G. Brognon (df), G. S. de Carvalho (eg)
Australia--G. N. Alexander (cg), R. C. Anderson (dh), G. Baker (abcdefgh), K. E. Bullen (b), H. G. Caine (cg), R. Culver (aceg), D. F. Glynn (g), L. T. Guy (ag), H. S. Hancock (abdfgh), J. H. Lavery (abcdefgh), C. H. Munro (g), H. Narain (ah), W. D. Parkinson (d), J. R. Philip (cg), L. S. Prior (abcdefgh), E. M. Shepherd (cg), R. F. Thyer (abcdefgh), D. T. Walsh (g), J. P. Webb (bh), F. W. Wood (bd)
Azores--J. Agostinho (bcdef), F. Machado (bf)
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[These are in the process of formation. The list will be published subsequently in the Transactions.]

- Executive Committee of the Union

- Standing Committees of the Union
  - International Participation
  - Statutes and By-Laws
  - Membership
  - Meetings
  - Nominations
  - Budget
  - Audit
  - Editorial and Publication

- Special Committees of the Union
  - Geophysical and Geological Study of Continents
  - Cosmic-Terrestrial Relationships
  - Award of the William Bowie Medal
  - Resolutions
  - Award in Terrestrial Magnetism and Electricity
  - Tellers
  - Advertising
  - Relations of American Geophysical Union with American Geological Institute
  - Relationship of American Geophysical Union to International Geophysical Year

- Regional Committees
  - North Central Regional Committee
  - Pacific Northwest Regional Committee
  - Pacific Southwest Regional Committee
  - Mid-Pacific Regional Committee

- Representatives
  - American Association for the Advancement of Science, Representatives on the Council
  - American Geological Institute, Board of Directors
    - Government Relations Committee
  - National Research Council, Division of Earth Sciences
  - National Research Council, Division of Physical Sciences
  - U. S. National Committee for the International Geophysical Year

- Committees of the Sections
  - Geodesy
    - Executive Committee
    - Resolutions
    - Program
    - Nominations
  - Seismology
    - Executive Committee
    - Resolutions
    - Nominations
  - Meteorology
    - Executive Committee
    - Upper Atmosphere
    - Atmospheric Diffusion
    - Atmospheric Chemistry
    - Cloud Physics ?
    - Chemical Meteorology
    - Interactions of the Atmosphere with the Sea (joint committee with the Section of Oceanography and the American Meteorological Society)
    - Nominations
    - Program
  - Terrestrial Magnetism and Electricity
    - Executive Committee
    - Nominations
    - Resolutions
  - Oceanography
    - Executive Committee
    - Nominations
    - Interactions of the Atmosphere with the Sea (see above under Meteorology)
  - Volcanology, Geochemistry, and Petrology
    - Executive Committee
    - Nominations
  - Hydrology
    - Executive Committee
    - Program
    - Awards
    - Nominations
    - Permanent Research Committees
      - Precipitation
      - Erosion and Sedimentation
      - Evaporation and Transpiration
      - Surface Water
      - Snow, Ice, and Glaciers
      - Ground Water
  - Tectonophysics
    - Executive Committee
    - Nominations

List of Publications

[Arrangements are being entered into with a reprint company to have back numbers reprinted, most of which are now out of print. Watch Special Announcements in the Transactions for further details. The Transactions from 1954 to the present are all still available, but as of July 1, 1957, it is anticipated that the Transactions for 1954 will be turned over to the reprint concern. Watch Special Announcements in the Transactions also for further information regarding this matter.]

Volume No.	Year	Title	No. pages	Price postpaid, volume
1	1920	Transactions (Reprint and Circular Series, National Research Council No. 11)	57	
2	1921	Transactions (Bull. National Research Council, No. 17)	108	
3	1922	Not published	..	
4	1923	Transactions (Bull. NRC, No. 41)	150	
5	1924	Not published	..	
6	1925	Transactions (Bull. NRC, No. 53)	80	
7	1926	Transactions (Bull. NRC, No. 56)	134	
8	1927	Transactions (Bull. NRC, No. 61)	297	
9	1928	Transactions (Bull. NRC, No. 68)	103	
10-11	1929-30	Transactions (all Sections)	314	
12	1931	Transactions (all Sections)	229	
13	1932	Transactions (all Sections)	401	
14	1933	Transactions (all Sections)	521	
15	1934	Transactions Part I (all Sections except Hydrology)	258	(See note near top of this page)
	1934	Transactions Part II (Hydrology)	376	
16	1935	Transactions Part I (all Sections except Hydrology)	364	
	1935	Transactions Part II (Hydrology)	166	
17	1936	Transactions Part I (all Sections except Hydrology)	260	
	1936	Transactions Part II (Hydrology and Regional Meetings, Hydrology)	304	
18	1937	Transactions Part I (all Sections except Hydrology)	264	
	1937	Transactions Part II (Hydrology and Regional Meetings, Hydrology)	300	
19	1938	Transactions Part I (all Sections)	585	
	1938	Transactions Part II (Regional Meetings, Hydrology)	159	
20	1939	Transactions Part I (Regional Meetings, Hydrology)	140	
	1939	Transactions Part II (Symposium on floods)	94	
	1939	Transactions Part III (all Sections except Hydrology)	250	
	1939	Transactions Part IV (Hydrology)	257	
21	1940	Transactions Part I (Stanford University, Regional Meetings, Hydrology)	144	
	1940	Transactions Part II (Washington Annual Meetings, all Sections)	632	
	1940	Transactions Part III (Richmond Symposium and Seattle Regional Meetings, Hydrology)	285	
	1940	Transactions Part IV (Columbus symposia: Applications of mathematics in the Earth sciences and Hydrologic problems in the Ohio and Michigan basins)	86	
22	1941	Transactions Part I (Sacramento Regional Meeting, Hydrology)	216	
	1941	Transactions Part II (Washington Annual Meetings, all Sections except Hydrology)	368	
	1941	Transactions Part III (Washington Annual Meeting, Hydrology)	452	
23	1942	Transactions Part I (Dallas and Pasadena Regional Meetings, Hydrology)	172	
	1942	Transactions Part II (Washington Annual Meetings, all Sections)	570	

Volume No.	Year	Title	pages	Price postpaid, volume
24	1943	Transactions Part I (Washington Annual Meetings, all Sections except Hydrology)	332	(See note near top of page 89)
	1943	Transactions Part II (Washington Annual Meeting, Hydrology)	454	
	1943	Transactions Part III (Corvallis Regional Meeting, Hydrology, and Western Snow Conference) and Addendum.	105	
25	1944	Transactions Part I (Berkeley Regional Meeting, Hydrology, and Western Snow Conference)	187	
	1944	Transactions Part II (Washington Annual Meeting, General Assembly, Geodesy, Seismology, Minutes of all Meetings)	203	
	1944	Transactions Part III (Washington Annual Meeting, Meteorology)	138	
	1944	Transactions Part IV (Washington Annual Meeting, Terrestrial Magnetism and Electricity, Oceanography, Volcanology, and Tectonophysics)	142	
	1944	Transactions Part V (Washington Annual Meeting, Hydrology: Reports)	160	
	1944	Transactions Part VI (Washington Annual Meeting, Hydrology: Papers)	236	
26	1945	Three bimonthly numbers starting with August	482	
27	1946	Six bimonthly numbers	926	
28	1947	Six bimonthly numbers	980	
29	1948	Six bimonthly numbers	956	
30	1949	Six bimonthly numbers	950	
31	1950	Six bimonthly numbers	968	
32	1951	Six bimonthly numbers	964	
33	1952	Six bimonthly numbers	956	
34	1953	Six bimonthly numbers	986	
35	1954	Six bimonthly numbers, $2.00 each	1026	$ 9.00
36	1955	Six bimonthly numbers, $2.00 each	1132	9.00
37	1956	Six bimonthly numbers, $2.00 each	812	10.00
38	1957	Six bimonthly numbers, $2.00 each; subscription for calendar year, $10.00.		
Monograph Series				
1	1956	Antarctica in the International Geophysical Year (with 42 × 42 inch map of the Antarctic).	134	6.00
Special Publications				
	1920-44	Index (combined author and subject), volumes 1-25.	144	4.00
		Bibliography of Hydrology, United States of America:		
	(1937)	Years 1935 and 1936	78	0.30
	(1938)	Year 1937	68	0.30
	(1939)	Year 1938	78	0.30
	(1940)	Year 1939	86	0.50
	(1941)	Year 1940	90	0.85
		Years 1941-1950 available through Government Printing Office, Washington, D. C., at a price of $1.75	408	
		Years 1951-1954 available through Government Printing Office, Washington, D. C., at a price of $1.25	208	
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	1950	September 10, 1950 (Part 2 of October 1950)	116	1.50
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Reconnaissance Study of Erosion and Deposition Produced by the Flood of August 1955 in Connecticut

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Abstract—A large area in the valley bottoms in Connecticut was inundated by the flood of August 1955. Relative to the total area flooded that part permanently modified by the flow was surprisingly small. Although great in some places, the distribution of these permanent modifications of channel and flood plain was spotty.

Erosion of the channel and valley bottom appears to have been most severe in narrow, steep valleys. Environments of deposition were diverse. They appeared to be related to rate and direction of flow, quantity and size of sediments locally available, and in some cases to the presence of vegetation. Most of the coarse sediment deposited in the valley appears to have been derived from local sources such as valley walls and terraces composed of glacial outwash and till and flood plains containing considerable gravel. Fine sand predominated in most of the sediment deposited.

Considering the magnitude of the runoff, the quantity of fine sediment transported or deposited by the flood was small. The maximum observed concentration was 473 parts per million in Scantic River at Broad Brook. Newly deposited fine sediments are thin or absent on the flood plains of many valleys which were beneath 20 ft of slow-moving flood waters. The paucity of deposition in such ideal depositional environments also indicates that the flow did not have a high concentration of fine sediments. A number of boulders five to seven feet in diameter were moved by flood waters in reaches in which smaller gravels were undisturbed.

Severe erosion in the uplands was minor. In this reconnaissance we saw little evidence of newly formed gullies and no areas of severe sheet erosion. This was the case in both woodland and pasture land. Large amounts of subsurface flow and relatively unerodible ground are presumed to be responsible for the absence of erosion.

Introduction—During August 1955, parts of the northeastern United States from Maryland to Massachusetts were visited by catastrophic floods. These floods resulted from excessive rainfalls associated with movement of hurricanes through the area. In Connecticut as much as 26 inches of rain fell during the month, 18 inches of it falling in a period of four days. The meteorology and hydrology of these floods is described in reports published by the *U. S. Weather Bureau* [1955] and the *U. S. Geological Survey* [1956].

This report is concerned with the physical effects produced on the natural landscape by these floods. Observations were made during a brief reconnaissance survey of a number of river valleys in Connecticut which experienced severe flooding during this period. During a three- to four-week period shortly after the floods, indirect determinations of discharge were made, and the data discussed here were collected. Figure 1 shows the location of some of the principal valleys studied. To illustrate the physical effects of an extraordinary flood, detailed observations were concentrated in the drainage basin of the Farmington River which experienced its highest flood of record.

Damage to urban structures, highways, or bridges is well documented elsewhere and is discussed here only as it relates to general principles of erosion and deposition in natural areas.

Condition of the upland—Both the quantity of rain and its intensity during 24-hour periods in northeastern Connecticut were extraordinary. However, in the area covered by our reconnaissance survey, we found no evidence of newly formed landslides or gullies, or of hillsides showing the effects of severe sheet erosion. As an example, the headwaters of Bissell Brook, 2¼ mi southwest of Granby are characterized by high relief with slopes up to 35 or 40° covered with hardwood forest, where 12 inches of rain fell on this area between August 17 and 19, 1955, the surface of the ground outside the swath of the stream was un-

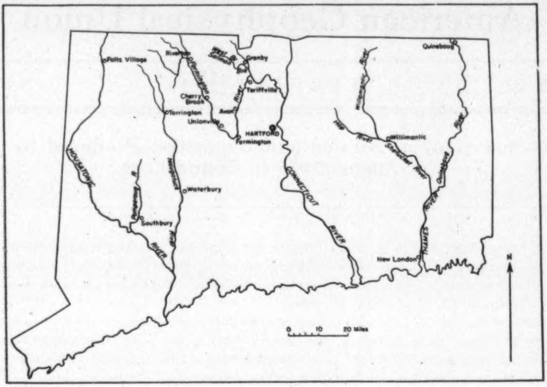
Falls Village
Riverton
Farmington
West Br.
Granby
Brook
Bissell
Cherry Brook
Tariffville
Torrington
River
Avon
Unionville
HARTFORD
Farmington
Quinebaug
Willimantic River
Hop River
Willimantic
Shetucket River
River
Quinebaug
HOUSATONIC
Naugatuck
Pomperaug R.
Waterbury
Southbury
River
RIVER
CONNECTICUT
RIVER
RIVER
THAMES
New London
N
0 10 20 Miles

FIG. 1 – Map of Connecticut showing principal streams investigated

altered. Heavily grazed hillsides near Granby and Avon showed a similar absence of erosion features. The lack of erosion suggest both a high infiltration capacity and considerable subsurface flow.

In contrast, in the small headwater streams themselves, such as tributaries to Bissell Brook, large cobbles and boulders were moved by flood waters. The channels consist of alternating pools and riffles, successive riffles being 30 to 40 ft apart. During the flood one such stream with a drainage area of 0.23 sq mi, flowed with a depth of about five feet and a top width of approximately 30 ft on a four per cent grade. After the flood had subsided the alternating pools and riffles remained. The clean-swept appearance of the pools suggested that the larger boulders had been displaced across the pool and lodged in the riffle.

Along with the absence of new gullies and landslides, pre-existing paths for concentrating water carried considerable amounts of soil and rubble during the flood. Abandoned roads and drainage ditches appear to have provided efficient runoff channels.

Where such headwater gullies debouched on flat terraces or flood plains within the larger valleys, they deposited the familiar debris fans. Boulders and cobbles in great quantity were transported by Thorp Brook near Roosterville, Mass. and deposited on a terrace adjacent to the West Branch Farmington River. The size of the material and details of the flow are given in Table 1. Similar debris fans associated with pre-existing channels or gullies were observed on the Quinebang River north of Quinebang and on the Farmington near Napaug Reservoir.

Channel widening—Figure 2 shows six cross sections beneath cableways at gaging stations of the U. S. Geological Survey on streams having drainage areas between 76 and 630 sq mi. Some cross sections are shown prior to the flood of 1938 as well as subsequent to that event in order to eliminate changes which might have been associated with previous high water rather than with the present flood. Despite the magnitude of the flood, none of these sections shows evidence of widening by the flood of August 1955. Although they provide at best, a meager record, the fact that they are well documented perhaps gives them added significance.

The bankfull channel of Bissell Brook near Granby, a typical small stream, is approximately ten feet wide and two feet deep. During the flood, water flowed four to five feet over the surface of the flood plain. Despite the quantity of water and the velocity of flow (sufficient to move a quartz boulder 0.7 x 0.5 x 0.5 ft) during the flood, the permanent channel was left largely undisturbed. This may result from the fact that during this high flood a large percentage of the discharge passed over the flood plain rather than through the main channel.

In contrast, considerable widening of the channel of Lewis Atwood Brook took place near Wood bury, Conn. Widening here appears to be related to

TABLE 1 – *Size of boulders moved by flood waters and some conditions of flow*

River and location	Size of boulder	Drainage area	Flood discharge	Slope	Estimated velocity	Depth of flow	Median size of bed material	Composition	Evidence of movement
	ft	sq mi	cfs		ft/sec	ft	ft		
East Branch Naugatuck R., ½ mile north of Torrington, Conn.	9.0 × 5.0 × 4.0	10	6,210	0.050	9	10	1.7	Granite	Local resident showed previous location, moved 80 ft, water stain shows previous orientation.
Farmington R., Unionville, Conn.	3.5 × 2.0 × 1.0	370	140,000	0.00012	...	25	0.5		Displaced over algae, covered median sizes.
West Branch Farmington R. below Riverton, Conn.	1.5 × 1.0 × 0.7	216	57,200	0.002	...	14	0.8	Quartz gneiss	Displaced over algae, resident noted 4 × 3 × 2 boulder not moved by flow.
Thorp Brook, Roosterville, Mass.	1.5 × 1.3 × 0.9	2.3	12,000[a]	0.067	...	5	1.0[b]	Gneiss	Debris fan over road.
Same	1.8 × 1.7 × 0.9				...				Same
West Branch Farmington R. near New Boston, Mass.	3.3 × 2.7 × 1.7	92	35,000	0.007	11	11	.4	Granite	Moved at least 15 ft from original position in bed over young willows, 0.7-ft size also moved.
Same	3.6 × 3.3 × 3.2			0.007				Granite	Resting on willows near edge of channel (see Fig. 8).
West Branch Salmon Brook 1½ miles northwest of West Granby, Conn.	3.0 × 2.5 × 1.7	5.2	5,000[a]	0.025	7	11	1.3[b]	Schist	Overlying uprooted trees (see Fig. 3).
Same	5.5 × 3.3 × 1.9			0.025				Schist	Turned up on edge.
Quinebaug R. near Quinebaug, Conn.	1.6 × 1.0 × 1.2	157	49,300	0.002	7	10	0.2	Quartz	Scoured from beneath flood plain
West Branch Salmon Brook near Granby, Conn.	0.5 × 0.4 × 0.3	15	8,250[a]	0.010	...	10	0.3	Quartz	Deposited on terrace surface eight feet above channel bed (see Fig. 10).
Bissell Brook 2½ miles south of West Granby, Conn.	7.0 × 3.5 × 3.5	1.1	2,000[a]	0.040	...	...	2.0[b]	Schist	Moved 25 ft, local resident showed previous location, water stain shows previous orientation.
Same	5.0 × 3.0 × 2.0				...	...	...	Schist	Leaning against tree.

[a] Discharge estimated from drainage area-discharge relation for flood of August 1955.

[b] Estimated

deposition by the flood of coarse boulders which forced the flow against the channel banks.

In narrow valleys where one of the channel banks may be the valley wall, a different type of channel widening occurs. Erosion of such valley walls and associated channel widening occurred in several valleys inspected by us.

Along the west bank of the Farmington River between Burlington Brook and Unionville the river removed several miles of highway and railroad track paralleling the stream. Several weeks after the flood the right bank of the stream had already been pushed back to its former position by placement of a new highway fill. Many locations in Naugatuck valley experienced similar bank erosion within relatively narrow valleys.

Care is often required in interpreting the observations of widening produced by erosion of either natural or man-made valley walls. Widening along the Farmington River, for example, is most pronounced on the outer or concave banks of the channel. Where the flow at such points impinged upon a man-made fill, the channel was temporarily widened. It is quite possible that if the embankment were not replaced after each flood the stream would permanently occupy its new position and readjust its width by depositing on the opposite convex bank. The presence of the embankment, then, which is continuously maintained against encroachment by the river, forces the stream to occupy both a narrower channel and a position toward the convex bank which it might not occupy under natural conditions.

Erosion of steep valley walls of glacial till and outwash adjacent to the stream channel of West Branch Salmon Brook between East Hartland and West Granby was particularly severe (Fig. 3). The mean velocity in parts of this reach was on the order of seven feet per second (Table 1). Confined flows 10 to 15 deep reach well up on the valley

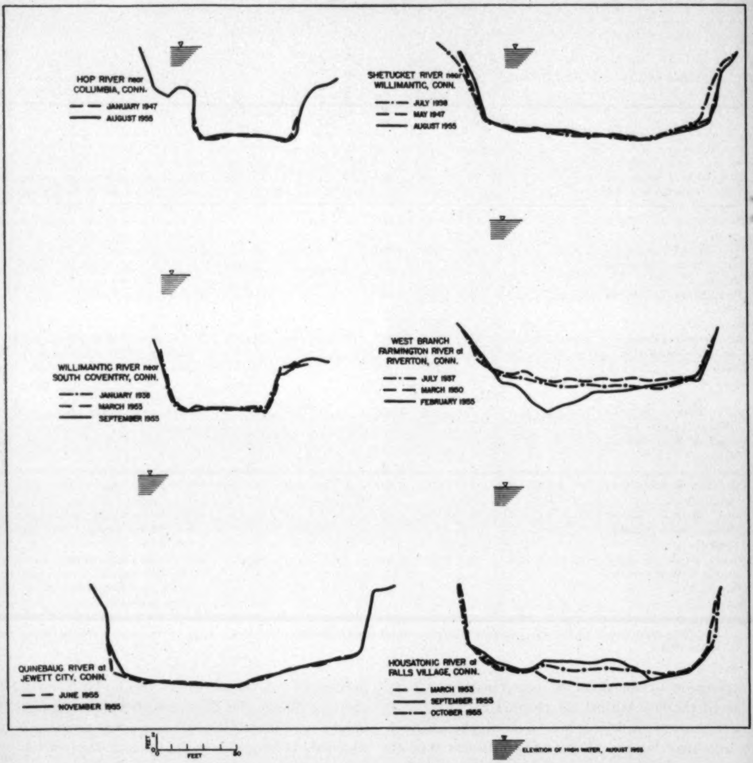

FIG. 2 – Cross sections of channels at cableways before and after flood of August 1955

walls producing severe erosion. The river washed out four or more bridges in this reach alone, and in places removed a vertical slice of sediment of ten or more feet thick from the walls. Because of the instability of the high cut banks the increased channel width will probably not be permanently maintained.

Limited data and observations indicate that in general this flood did not produce extensive widening of channels in broad flood plains. In contrast, however, lateral erosion by this catastrophic flood was especially demonstrable in narrow valleys where the channel width was materially, if only temporarily, increased by the flood.

Channel deepening—Although there are fluctuations in the depth of the channels at specific points, of the streams shown in Figure 2 for which we have the most accurate data, only the West Branch Farmington River at Riverton deepened its channel significantly during the flood. At the Housatonic at Falls Village, several feet of sand was deposited on the coarser bedded channel. As the cross sections show (Fig. 2) subsequent lesser flows are progressively removing this finer material reestablishing the former bed level. The data also indicate that at some sections, fluctuations in depth produced by moderate flows and annual floods subsequent to 1938 and prior to August

1955, were as great as or greater than those produced by this record-breaking flood.

Some evidence is also available on deposition and scour resulting from the large flood in data obtained by the U. S. Geological Survey at gaging stations. For a given discharge the stage of the flow is governed by a control which may be a gravel bar or riffle, downstream channel reach, or perhaps a concrete sill. If a control is scoured during a flood, the gage height previously associated with a particular discharge will now be associated with a larger one. On the other hand, if the channel experienced a net fill as a result of the flood, then one should expect the reverse. Although the data in Table 2 are of limited value because many of the controls are not readily altered by the flow, shifts in control which took place during the flood of August 1955 are interpreted in terms of scour and fill.

Of the gaging stations in Table 2 having relatively natural controls, about half show neither scour nor fill. Filling is indicated at all of the controls which experienced changes. Other cross sections studied in detail did not show a net scour and thus could not represent typical sources for the net fill experienced at some of the gaging stations. It may be concluded that (1) the material was not derived from the channel bed, or (2) the amount of material moved was relatively small. This view is supported by the small amount of material deposited on the controls. Because no change took place at more than half of the stations considered, we cannot conclude that either scour or deposition occurs universally in the river bed during or after the flood.

Documented cross sections present little evidence of major channel deepening resulting from floods. Local rearrangement of bed material produced some deposition on previously existing riffles or rises in the channel bed. These data indicate that the flood did not alter a large proportion of the natural river channel. In places this lack of change may be related to bypassing of the main channel by the high water. Elsewhere the controlling factor may have been the inability of the flood flow to erode armored beds of gravel, even of sizes as small as ¾ inch (see below).

FIG. 3 – West Branch Salmon Brook near West Granby, Conn. showing erodible valley wall and large boulders moved during flood; valley bottom is 70 feet wide; note man to left of center of figure.

Detailed descriptions of deposition and erosion on flood plains and terraces—To aid in attempting to understand the processes producing the complex distribution of erosion and deposition in valley bottomlands during a flood, reaches in two valleys which were struck by the flood are described in detail. These represent extremes in the degree of alteration produced by the flood and thus are not representative of the changes wrought over the inundated area as a whole.

Two cross sections were made on the right bank and flood plain in a curving reach of the Farmington River opposite the mouth of Cherry Brook, 1½ miles north of Collinsville, Conn. (Fig. 4). The river here has a drainage area of 350 sq mi. Profiles of the land surface prior to the flood were

TABLE 2 – *Effect of flood of August 1955 on scour or fill at gaging stations in Connecticut*

Gaging station	Drainage area	Flood stage	Flood discharge	Scour or fill on control
	sq mi	ft	cfs	
Willimantic R. near South Coventry*	121	18.7	16,300	Fill
Hop R. near Columbia	76.2	15.10	4,520	No change
Safford Brook near Woodstock valley	4.08	6.7	780	No change
Mount Hope R. near Warrenville	29.1	10.4	1,900	No change
Natchaug R. at Willimantic	169	3.5	400	No change
Little R. near Hanover	29.8	6.5	1,400	No change
Shetucket R. near Willimantic	401	17.35	21,300	No change
Quinebaug R. at Quinebaug	157	19.0	18,000	Fill
Scantic R. at Broad Brook	98.4	19.9	15,000	Fill
Still R. at Robertsville	84.4	16.48	32,000	Fill
Pequabuck R. at Forestville	45.2	13.23	11,000	Fill
Farmington R. at Rainbow	584	23.5	62,000	No change
Blackberry R. at Canaan	48.2	13.02	10,500	No change
Tenmile R. at Gaylordsville	204	14.9	17,000	No change
Housatonic R. at Gaylordsville†	994	18.5	54,000	No change
Still R. near Lanesville	68.5	11.9	4,870	No change
Shepaug R. near Roxbury	133	17.22	18,500	Fill
Pomperaug R. at Southbury	75.3	21.8	12,000	No change
Leadmine Brook near Thomaston	24.0	13.1	4,200	Fill

* Under bridge, washed out road fill.

† Rock ledge.

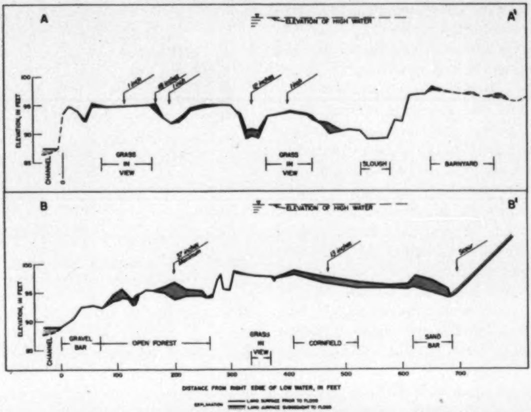
A
ELEVATION OF HIGH WATER
A'
ELEVATION, IN FEET
100
95
90
85
CHANNEL
0
1 inch
12 inches
GRASS IN VIEW
SLOUGH
BARNYARD
B
ELEVATION OF HIGH WATER
B'
Scour
GRAVEL BAR
OPEN FOREST
GRASS IN VIEW
CORNFIELD
SAND BAR
0
100
200
300
400
500
600
700
DISTANCE FROM RIGHT EDGE OF LOW WATER, IN FEET
EXPLANATION
LAND SURFACE PRIOR TO FLOOD
LAND SURFACE SUBSEQUENT TO FLOOD

FIG. 4 – Cross sections of flood plain and terrace levels on Farmington River at Cherry Brook, Conn. following flood of August 1955

determined from holes dug at closely spaced intervals across the section. Section AA is 100 ft downstream from the mouth of Cherry Brook. Section BB is 500 ft upstream. At the peak of the flood, water flowed 12 to 20 ft deep over the entire area.

Although section AA traverses a relatively open area of the flood plain largely covered by grass, while much of section BB is more forested, several comments are common to both of them.

(1) There are two distanct levels in each section. The lower, presumably the active flood plain adjacent to the stream channel, is approximately seven feet above low water. The upper surface or terrace is approximately ten feet above low water (see Table 3).

(2) Considerable differences in elevation existed on the flood plain caused by the presence of overflow sloughs or channels prior to the flood. Differences of elevation of three to five feet over lateral distances of 20 ft were common.

(3) Some of the overflow channels or sloughs received deposits of coarse and medium sand to depths of one foot. At such locations the relief was materially reduced. In general, the flow appears to have followed these former overflow channels and hence to have maintained the preexisting surface relief.

(4) No deposition took place at many points in cross section *AA*, and at some points in section *BB* (Fig. 4). A veneer of sand often gives the impression of more deposition than actually occurred.

(5) The new deposits consist principally of well sorted medium and fine sand. It is worth emphasizing that all of these are unusually well-sorted alluvial deposits (Table 4). Although sorting is somewhat poorer in the underlying sediments, in

TABLE 3 – *Elevations of flood plains, terraces, and high water, August 1955, Connecticut flood area*

River and location	Elevations of flood plain and terraces in range of elevations above low water					Estimated elevation of high water August 1955
	1–5 ft	5–10 ft	10–15 ft	15–20 ft	20–30 ft	
Willimantic River, South Coventry	1.3 2.3				22	14
Pomperaug River, Southbury	3.7	9			26	18
West Branch Farmington River, Pleasant Valley			13		23	18
Farmington River, Unionville			12	18		30
Farmington River above Unionville			11	18?		30
Farmington River, Cherry Brook		7	10			23
West Branch Salmon Brook near Granby	4	7				10
Quinebaug River near Quinebaug	4	8				17
West Branch Farmington River near New Boston, Mass.	3.5	9			23	11
Farmington River above Collinsville		6.5	11		22	30

TABLE 4 – *Size analyses of sediment samples from Connecticut flood area*

Sample	River and location[a]	Median diameter	First quartile D_{25}	Third quartile D_{75}	Sorting coefficient $\sqrt{D_{75}/D_{25}}$	Cross section	Description of sample
		mm	mm	mm			
1	Farmington R. at Cherry Brook	0.18	0.14	0.23	1.28	AA	Flood deposit 2–6 inches below surface, Station 166
2	Same	0.18	0.135	0.225	1.29	AA	Flood deposit 9–11 inches below surface, Station 166
3	Same	0.23	0.14	0.31	1.49	AA	Underlying material 18 inches below surface, 4 inches below previous ground surface, Station 166
4	Same	0.22	0.17	0.29	1.31	AA	Flood deposit surface sample 1 inch thick, Station 113
5	Same	0.21	0.115	0.33	1.70	AA	Underlying material 10 inches below surface, 9 inches below previous ground surface, Station 113
6	Same	0.18	0.14	0.23	1.28	BB	Flood deposit 5–7 inches below surface, Station 255
7	Same	0.17	0.125	0.22	1.33	BB	Underlying material 11–13 inches below surface, 1–3 inches below previous ground surface, Station 255
8	Same	0.09	0.051	0.12	1.53	BB	Flood deposit 14–16 inches below surface of "sand bar" Station 623
9	Farmington River at River Glen	0.23	0.175	0.28	1.26		Flood deposit on surface
10	Farmington River at Farmington	0.021	0.013	0.031	1.54		Flood deposit at bend in river
11	Quinebaug R. near Quinebaug	0.32	0.25	0.42	1.30	Downstream	Flood deposit in cornfield 40 ft. from left edge main channel
12	Same	0.16	0.084	0.25	1.72	Downstream	Flood deposit on grass 250 feet from left edge main channel
13	Same	0.030	0.017	0.046	1.65	Downstream	Flood deposit on grass 390 feet from left edge main channel

[a] All in Connecticut.

both sections *AA* and *BB* the flood deposits are similar to the underlying material (Table 4). Those differences that do exist are not consistent from one sample location to another.

In section *BB* a maximum thickness of 37 inches of sand was observed at station 200. Deposition in section *BB* exceeded that in *AA*, while farther upstream from *BB* a blanket of sand was deposited by the flood.

The larger volume of material deposited at section *BB* is perhaps attributable to the forest vegetation although the woodland is relatively open and the ground cover primarily grass. It is also possible that the thicker deposit at section *BB* is related to the direction of flow during waning stages of the flood when section *BB* perhaps was a locus of deposition on the convex side of the bend.

An average of about one foot of sand was deposited in a cornfield (section *BB*, Sta. 400–520). Inasmuch as the stalks remained upright this deposit may be attributed to the trapping effect of the corn. Perhaps of equal importance, however, was a wooded spur of high ground protruding into the valley upstream which reduced the velocity across the field below.

These sections on the Farmington River at Cherry Brook indicate that as one might expect pre-existing topography, relative orientation of valley and flow, vegetation, and composition of available sediment all played a part in determining the conditions of deposition and scour resulting from the flood.

Figure 5 is a cross section of the West Branch Salmon Brook 2.2 miles southwest of Granby, Conn. The drainage area at this point is nine square miles. Prior to the flood the main channel flowed through a moderately dense forest cover to the left at station 600. At the peak of the flood, water flowed approximately three feet deep over the entire section. When floating trees and other debris partly blocked the main channel at the upper end of the reach the water, seeking an

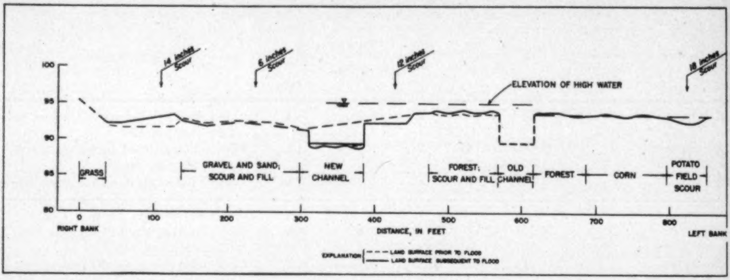

FIG. 5 – Cross section of West Branch Salmon Brook near Granby, Conn., following flood of August 1955

alternate course across the flood plain and terrace, eroded a new channel approximately 3½ ft deep and 80 ft wide (Fig. 5).

The new channel cuts across the chord of a bend but is not a typical meander cutoff inasmuch as the new channel leaves the old at an abrupt angle. Although large trees obstructed the flow, their effectiveness was enhanced by the presence of boards and fragments of old wooden structures. Such a cutoff is a natural and repetitive occurrence but not a predictable one. Although similar ones took place elsewhere, our observations indicate that permanent cutoffs produced by the flood were the exception rather than the rule. The effects of the flood on the West Branch Salmon Brook are best described by referring to the cross section (Fig. 5).

The lower part of the stratigraphic section through the flood plain exposed in the channel bank contains coarse gravel overlain by fine sand and silt. The contact between the two is exceedingly irregular. In some places gravel lies within a foot of the old surface; elsewhere it is two to three feet below the surface. The pre-flood surface of the flood plain was eroded as much as a foot in places (Fig. 5). At these points fresh gravel was deposited by the flood subsequent to the period of scour rest upon older gravel in the flood plain. Elsewhere fresh cobbles and gravel were deposited on top of the finer sediments of the flood plain. The contact between the older sediments and the newly deposited sand and gravel lies from about one foot to six inches below the pre-flood surface of the plain. The original surface at station 460 is about 1.5 ft higher than the contact. Thus the gravel-capped area on the right bank of the new channel is predominately one of scour.

In contrast to the reduction of relief observed on the Farmington River, between stations 480 and 570 (Fig. 5) differences in elevation on the flood plain were increased by the flood. This came about through deposition of parallel ridges of sand aligned in the direction of flow with alternating swales between them produced by moderate scour. Farther to the left of the old channel scour was particularly severe along rows of potatoes parallel to the overflow.

Limited deposition of sediment along Farmington River between Farmington and Tariffville—The preceding description emphasized the extreme alteration produced by the flood in West Branch Salmon Brook and Farmington River at Cherry Brook. Contrasting conditions are perhaps illustrated by the following observations in the Farmington River valley between Avon and Tariffville, Conn. Shortly after the flood, parts of the valley which had been beneath 20 ft of water appeared to be virtually unaffected by the flood. Indeed in many areas four weeks after the event, it would have been impossible to tell that the area had been flooded save where houses and other works of man showed clearly the damage produced by inundation. To test these impressions in one valley a reconnaissance survey was run.

Between Tariffville and Avon, a distance of 7.5 mi along the river valley, 3.4 sq mi of land had been inundated. The area of inundation was roughly determined by planimetering on a topographic map. Each linear mile parallel to the valley included on the average 0.45 sq mi of flooded area. In each segment along the valley by observation or examination we estimated the percentage of the area covered by sediment and the thickness of the deposit. The length of the segment was determined from odometer readings. To compute the area covered by sediment the odometer mileage was multiplied by the average area inundated per linear mile of valley, and this product was multiplied by the estimated percentage of the area observed which was covered by sediment.

At a few localities we examined the deposits in detail. The estimates of thickness of very thin deposits are obviously rough. This is particularly true in areas in which no deposition is reported. In such places it is conceivable that a thin veneer of sediment of the order of less than 0.02 foot which was not distinguishable at the time of the survey may have existed. The following results are put forth with this qualification in mind.

Deposition appears to have occurred on 15 pct of the 3.4 sq mi inspected in the Farmington valley. Of this 15 pct, about 25 pct was estimated to have been covered by a thickness less then 0.05 foot of sediment and approximately 16 pct by a thickness of 0.1 foot or greater. Thus, not only was the area of deposition small but within the area the deposit is exceedingly thin. Because of the spottiness of the deposits, computation of a figure for the average thickness of deposition over the entire valley would not be justifiable. The relation of deposition to conditions of flow is illustrated in more detail by the following examples.

Near Farmington, Conn. the Farmington River makes an abrupt bend turning from southeast to north (Fig. 1). At this bend the valley is approximately 1.5 mi wide. During the flood the valley was inundated to a depth of 18 ft. The gradient of the river determined from a topographic map is only 0.0001. It is not surprising that in this ideal setting basin there was a deposit of silt (Table 4, sample 10) as much as one foot thick. Less than one mile upstream, however, inundation occurred to similar depths (see Fig. 6) and despite the low gradient, wide valley, and depth of inundation, the area shows little or no effects of flooding (Fig. 7). The 'untouched' look of the flood plain is remarkable. It was described in our reconnaissance survey as an area of no deposition.

On the left bank of the Farmington River one mile upstream from Route 44 near Avon, Conn., the high-water mark on a barn is 19 ft above the level of the plain. Most of the area several weeks after the flood appeared untouched. In places scour was evident around the roots of corn and thin veneers of silt were observed adjacent to these points of scour. Despite such minor changes, the over-all aspect of the flood plain appeared unchanged by the flood.

Our observations of the Farmington valley suggest: (1) The total amount of sediment deposited by the flood was small. (2) Considering the ideal depositional environment provided by the flooded valley, one must conclude that the flow carried only a small concentration of sediment. The absence of erosion on the land gives weight to this conclusion. (3) The areas in which deposition took place are predominantly shallow depressions. (4) The thickness of the deposits where they occur is generally less than 0.05 foot.

Measurement of suspended sediment; Scantic River at Broad Brook—Suspended sediment is measured at only one station in the area flooded in Connecticut. Because water overtopped the bridge and sampling device on Scantic River at Broad Brook the record is incomplete. Nevertheless, the selected data in Table 5 show the range and fluctuations in concentration observed at specified times during the flood. (The complete record is published by the U. S. Geological Survey in annual reports, on Quality of Surface Water of the United States.)

The peak concentration on Scantic River occurred prior to the peak discharge. Although concentrations observed in this flood somewhat exceed the selected values observed in several other high

FIG. 6 – Farmington River in flood, Route 4 at Farmington, Conn., looking upstream; note isolated trees for comparison with Figure 7, photo courtesy of *Hartford Times.*

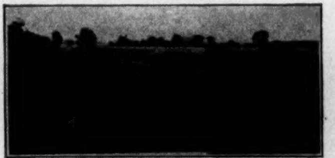

FIG. 7 – Farmington River four weeks after flood, same location as Figure 6, looking downstream

TABLE 5 – *Selected observations of concentration of suspended load, Scantic River at Broad Brook, Conn.*

Date	Time	Discharge	Concentration	Remarks
1955	h m	cfs	ppm	
Aug. 17	18 15	50	18	
Aug. 18	11 30	204	369	
Aug. 18	14 30	392	473	Maximum observed concentration
Aug. 18	17 30	703	28	
Aug. 20		4360	222	Maximum observed discharge[a]
1953				
Jan. 25		1430	187	
Jan. 26		1060	60	
Mar. 30		756	141	
Mar. 31		1040	98	

[a] Record does not include peak; peak determined from slope-area measurement, 13,300 cfs, August 19, 1955, 18h 00m.

flows (Table 5) the maximum measured concentration of 473 ppm associated with a discharge of 392 cfs is not high. The moderate concentrations observed perhaps support the conclusions arrived at indirectly from observations of erosion and deposition in the Farmington River valley.

The data in Table 5 clearly show the abrupt fluctuations in concentration associated with the flood. In a period of three hours on the afternoon of August 18, despite a continuously rising discharge, the concentration of the measured sediment dropped by a factor of 20. Such changes are probably related to differences in the distribution and intensity of rainfall but adequate data are not available for analysis.

Table 6 shows the size and sorting of the suspended sediment. The suspended material is roughly 10 to 20 times finer than the flood deposits (Table 4). The flood deposits are unusually well sorted whereas the suspended sediment is quite poorly sorted.

TABLE 6 – *Median diameter and sorting of suspended sediment, Scantic River at Broad Brook, Conn.*

Date	Time	Discharge	Median diameter	Sorting coefficient $\sqrt{D_{75}/D_{25}}$
1955	h m	cfs	mm	
Aug. 13	16 30	314	0.008	3.10
Aug. 13	18 30	350	0.021	3.08
Aug. 14	06 30	408	0.013	3.16
Aug. 18	11 30	204	0.005	...
Aug. 18	14 30	392	0.010	4.42
Aug. 18	19 00	763	0.010	4.12
Aug. 20	11 50	4,362	0.006	1.99
Aug. 20	15 30	3,138	0.004	3.64

Competence of the flood—Table 1 is a compilation of the sizes of boulders moved by the flood in channels having different discharges, slopes, velocities, and depths. The evidence of movement consisted of boulders overlying vegetation, or resting upon signs or tin cans, or of reports of local observers living adjacent to the stream who could identify with certainty the former position of the boulder in question. In the latter case the former position of the boulder could often be verified by the water mark on its surface or by a gap at the position which it formerly occupied.

The sizes of the boulders are the dimensions of three mutually perpendicular axes. The slope in most instances was derived from the topographic map. Where available the velocity is the mean velocity of the flow determined as the quotient of the discharge divided by cross-sectional area. The discharge, unless otherwise noted, is based on indirect determinations of the *U. S. Geological Survey* [1956]. The median diameter of the bed material was determined by pebble counts.

Some phenomenally large boulders were moved. The largest boulder of which we have a verifiable record is a nine-foot granite boulder moved by the flood in the East Branch Naugatuck River. The slope of this stream is steep and judging from the mean velocity, point velocities of 15 to 18 ft per second may well have existed in the flow.

Individual boulders moved by the flow were often large in comparison with the median size of the bed material (Fig. 8). Boulders two to eight times as large as the median size on the bed were moved in reaches where the median material did not move. In the Farmington River at Unionville, the presence of moss and algae covering the average size cobbles on the bed indicates that this smaller material was not moved by the flow, while boulders many times larger were moved over the gravel. The 'armored' character of such gravel beds has often been noted in the literature.

The fact that large boulders moved under conditions in which smaller stones did not suggests that a parameter relating the size of particle moved to the average of the material making up the bed, such as *Ippen* and *Verma* [1953] used in determining criteria for movement, may be particularly useful in dealing with transport of large particles in natural rivers.

Relation of flood stage to elevation of deposits—In West Branch Salmon Brook sand and even gravel were deposited on a terrace surface approximately seven feet above the bed of the channel. The high stages reached by a flood of this magnitude permit deposition at elevations well above the reach of the annual flood. *Jahns* [1947] has described such aberrant deposits which interrupt the depositional sequence in the flood plain and on top of the higher terraces.

Roughly three alluvial surfaces are indicated by the data from random valley cross sections given in Table 3. The lowest is at an elevation of about two to four feet; the next lies between 8 and 12 ft, and the highest surface in these cross sections lies somewhere between 18 and 23 ft. In most places the large flood of 1955 inundated both of the lower levels. In general, despite two to five feet of water over the 8- to 12-foot level, deposition and erosion on this surface were moderate. In some places, as for example on the 13-foot terrace remnant of the West Branch Farmington River at Pleasant Valley, there are scour holes several feet deep immediately adjacent to which are sand splays as much as a foot thick.

Jahns [1947] has established the fact that the floods of 1936 and 1938 in the Connecticut Valley in Massachusetts attained stages in excess of any of those in recorded history or in recent geologic past. This conclusion can probably be safely applied to the areas inundated in Connecticut as well. It has been established that the flood of August 1955 considerably exceeded the peaks attained by the 1936, 1938, and 1949 floods in the valleys described here [*U. S. Geological Survey*, 1956]. In a few valleys the stage was sufficiently high to result in deposition or scour on terrace surfaces not reached by previous high water.

Source and compositions of deposits—The town of Unionville, Conn., was devastated by the Farmington River during the flood. Where the current impinged upon the left bank of the river near Route 4 in Unionville, numerous houses were undercut and swept down the river. Where these houses stood, only a cleanly washed cobble and boulder terrace remains. This terrace, 11 ft above low water, corresponds to similar terrace elevations observed elsewhere in the basin (Table 3). Although the gravel appears to be a new deposit, its elevation suggests that a layer of material was removed from the surface of the existing terrace with small displacement of the terrace itself. Several hundred yards downstream sand was deposited on the flood plain. Inasmuch as trees eight inches in diameter were uprooted by the flow which local residents estimate had a velocity at the peak on the order of 20 mi/hr, deposition apparently took place on the falling stage of the flood. The small quantity of sand deposited suggests that the scoured terrace immediately upstream was a likely source for the sand.

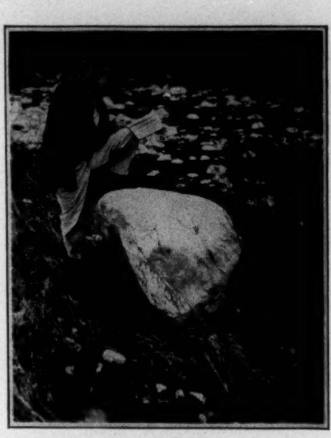

FIG. 8 – Boulder moved by flood of August, 1955, West Branch Farmington River near New Boston, Mass.; note smaller size of median bed material

Extensive deposition occurred on the flood plain of the Farmington River at River Glen. The swept angle of the trees as well as the removal of several houses testifies to the strength of the current. Banks of glacial outwash upstream below Unionville, eroded by flood waters, appeared to have provided the source of the deposit of coarse sand (Table 4, sample 9).

Several possible sources exist for the gravel deposits previously described at West Branch Salmon Brook near Granby: (1) gravels within the flood plain itself, (2) steep and readily erodible bank of sand and gravel 300 feet upstream, and (3) the severely eroded valley section (Fig. 3) three miles upstream. The intense scour of the pre-flood flood plain, the absence of coarse particles in the channel bed at the foot of the exposed bank, the absence of gravel and cobbles in the overflow section above the potato field, and lastly, deposits of sand and gravel in scour holes in the potato field apparently derived from the holes themselves,

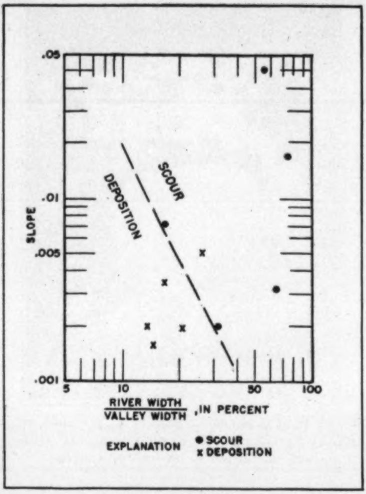

FIG. 9 – Conditions of deposition and scour related to slope and ratio of river width to valley width

suggest that again the deposits were locally derived.

Many man-made embankments and highway approaches were washed out or destroyed by the flood. In almost every case the material derived from these bridge approaches can be seen strewn out several feet below its source in the eroded fill. Good examples of this were observed by the authors on the Pomperaug River at Southbury, Conn., on French Creek near Putnam, on Willimantic River near South Coventry, and on Bissell Brook near Granby. In most instances it appears that local sources provided the bulk of the material deposited on the flood plains and terraces.

Factors controlling erosion and deposition by flood waters—In several reaches where either scour or fill was particularly evident, data were obtained on slope and relative width of channel and valley. In most cases slope and valley width were measured on topographic maps. The channel width was determined by measuring or by pacing. The meager data are plotted in Figure 9 simply to illustrate, as graphically as possible, any existing relationship.

The graph indicates that in general scour is related to steep slopes and narrow valleys. It appears that at a given slope where the channel is roughly from ⅕ to ⅓ of the valley width, there was a tendency for scour rather than deposition. Inasmuch as steep slopes and narrow valleys, which are associated in nature, both contribute to increased velocity and depth at a given high discharge, it is to be expected that such conditions would produce a tendency for scour rather than fill.

Direction of flow—Numerous sites were seen in the field at which the direction of the flow relative to the orientation of the valley as a whole exercised a controlling effect on conditions of sedimentation. One such case from the Quinebaug River is described below.

The dimensions and flow characteristics of an upstream and a downstream cross section of the valley of the Quinebaug River near Quinebaug, Conn., are given in Table 7. The sections are about 800 ft apart.

At the cross section upstream the flood scoured a channel six feet deep and 15 ft across, extending downstream about 200 ft from the narrowest section of the valley. The material eroded from the flood plain was deposited at the downstream end of this scoured channel.

As the flood flow expanded into the larger reach downstream, conditions of scour and deposition changed. Adjacent to the left bank of the channel there is an area of continued scour, although at the reduced velocity the flow was not sufficient to scour a major cut as it did upstream. Proceeding from this area of scour toward the left edge of the valley, the environment changed from one of scour to one of deposition. The sediments deposited by the flood become progressively finer to the left (Table 4, samples 11, 12, 13). The cross-sectional area of the upstream section is about one half of the downstream section (Table 7). If the flood discharge (*U. S. Geological Survey*, 1956] was evenly distributed in each of these cross sections, the mean velocity in the upstream section would be approxi-

TABLE 7—*Estimated flow conditions in cross sections on Quinebaug River near Quinebaug, Connecticut*

Cross section	Discharge	Total width of valley cross section	Total Area of valley cross section	Average velocity in cross section discharge area
	cfs	ft	sq ft	ft/sec
Upstream	49,300	430	4,900	10
Downstream	49,300	630	7,662	6

mately ten feet per second, while the mean downstream would be six feet per second. The high velocity is associated with scour. On the other hand, the 'mean' velocity at the downstream section is obviously not descriptive of conditions at different points across the valley. Judging from the scour adjacent to the channel, the main flow moved along the right edge of the valley. The flow expanding toward the left margin, however, appears to have had a different orientation and a much lower velocity. Those areas in which the flow diverged most markedly from the main current received the deposits of finest texture.

The irregularity of most valleys provides numerous local sedimentary environments. A large part of the flood flow may travel across a valley floor as a swiftly moving mass, while on either side of it the flow is virtually motionless. A protruding spur may force the main current to move obliquely across the valley producing a separation of flow and a quiet eddy in the lee of the spur. Thus orientation and direction of flow account for much of the diversity in sedimentation produced by a large flood.

Effect of vegetation—On the Farmington River at Cherry Brook, one foot of sand was deposited in a cornfield. On the flood plain of the Farmington near Avon, scour rather than deposition characterized the cornfield. On the Quinebaug River in the downstream section the cornfield was the site of both scour and deposition (Table 4), depending upon the lateral position within the valley. In addition, although the cornfield was scoured, deposition took place on the grassed areas (Table 4) which might have been expected to trap much less sediment. Similarly, on the left side of the upstream cross section of the Quinebaug River, despite little change in the density of the forest cover, three inches of sediment was deposited near the left margin of the flow while 100 ft toward the center of the flow no deposition or scour was observed within the forest. Here again the position of each point relative to the flow rather than the vegetation controlled the amount of deposition.

The effect of forest vegetation in inducing deposition was more clearly seen on an island near the center of the flow of the West Branch Farmington River, one mile south of Riverton. The small island supports a growth of deciduous and evergreen trees many of which are one to two feet in diameter, spaced approximately 10 to 20 ft apart. One inch to two feet of course and medium sand was deposited beneath the trees while in the channel adjacent to this tree-covered island, the flow was approximately 20 ft deep and moved boulders one foot in diameter.

It is difficult to generalize regarding the effect of vegetation on sedimentation during a flood. Other things being equal, that is, for example, where slope, valley width, and direction of channel flow are the same, deposition appears to be aided by vegetation. There are, however, many locations in the average stream valley where these other factors far outweigh the effect of the vegetation in controlling positions of scour and deposition.

Effect of changes in river stage—We observed one locality at which the sediments deposited by the flood provide some evidence of the effect of changing stage on flood deposition. On a seven-foot terrace adjacent to West Branch Salmon Brook near Granby (Fig. 10) six inches of cobble gravel were deposited on the old surface, and upon the gravel an additional 6 inches of course and medium sand was deposited. Their successive positions as well as the sharp contact between the two suggests that the gravel was transported at a high stage and velocity and that the sand was deposited later during recession of the flood.

Acknowledgments—We are indebted to L. B. Leopold for his assistance in the field, to B. L. Bigwood, District Engineer, Hartford, Conn., and to members of his staff. Personnel of the Surface and Quality of Water Branches of the U. S. Geological Survey provided us with much information regarding the flood. Both the *Hartford Courant* and the *Hartford Times* very kindly put at our disposal their extensive files of photographs of the flood. It is a pleasure to express our appreciation for this service.

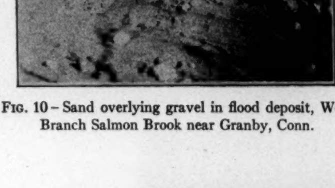

Fig. 10 – Sand overlying gravel in flood deposit, West Branch Salmon Brook near Granby, Conn.

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Correlation of Rainfall Intensity and Topography in Northern California

RAY K. LINSLEY

Abstract—As part of a long-range program on the hydrology of small watersheds, a correlation between the two-year, one-hour rainfall intensity at 126 recording rainfall stations in northern California and related topographic and climatic parameters has been made. The resulting correlation has a coefficient of correlation of 0.88 and a standard error of 0.067 inch/hour. With this relation, it is possible to show the variation of rainfall intensity over the area in much greater detail than has hitherto been possible from observed intensity data alone. This paper discusses the parameters employed, the methods of correlation, and the results obtained.

Introduction—One of the problems in any study of rainfall intensity is the limited number of stations with record suitable for frequency analysis. For a regional study, data are limited to the hydrologic network stations available since about 1940. After preliminary study, it was decided to limit this analysis to California north of 35° N to avoid introducing large scale climatic factors. In this area approximately 150 station records were available for use. After screening to eliminate records which were too short or were composites from several station locations the number was reduced to 126.

The maximum length of record was ten years and the average length substantially less. Consequently the two-year, one hour intensity was adopted as the best choice of a dependent parameter. Since clock-hour data were readily available, these were used although the maximum 60-min values would be somewhat higher. Occasional summer thunderstorms produce high-intensity rains in California. Because these storms are the result of quite different meterological processes, they were excluded from the analysis by using only the September through April period. Since most of these summer rains fall on dry ground and produce little runoff, this exclusion does not seem to affect the utility of the results.

The general technique utilized is that previously employed by *Spreen* [1947] *Burns* [1952], and others for relating mean annual or mean seasonal precipitation to topography. The coaxial method of graphical correlation [*Linsley* and others, 1949] was employed because of the flexibility it offers. Since a relatively large number of stations was to be analyzed, data were transcribed onto Keysort punched cards. These cards could be easily stratified and average values computed for each parameter as needed.

The complete study [*Linsley*, 1956] involved comparison of four alternative relationships. This paper reports only the one which seems to offer the best results.

Index daily rainfall—It is a logical assumption that, within a small region where the occurrence of rainfall at all stations is limited to about the same number of hours in a year, hourly intensities will bear some relation to mean annual precipitation. The study area is too large for strict adherence to this assumption and a parameter called index daily rainfall was defined by

$$\text{Index daily rainfall} = P/N_{0.25} \qquad (1)$$

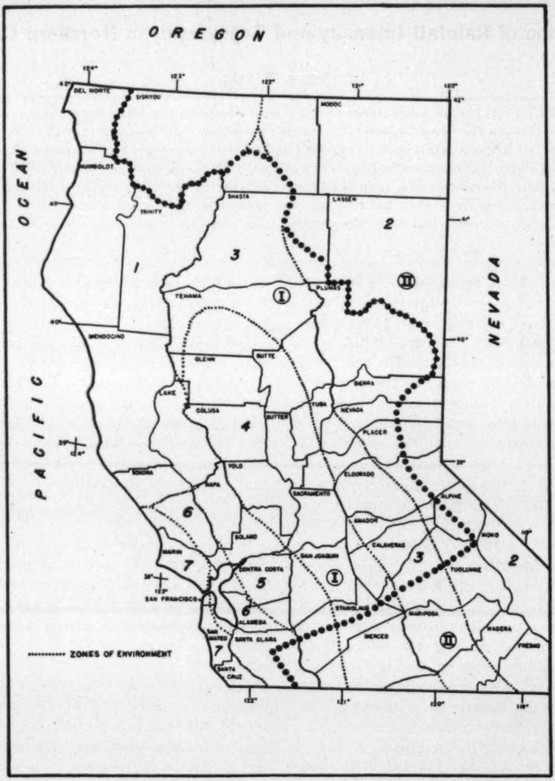
In this equation P is the normal (or average) September through April total precipitation and $N_{0.25}$ is the average number of days (September through April) with rainfall in excess of 0.25 inch.

It is recognized that this is not truly a topographic parameter. Its use in the relation limits estimates of intensity to points where values of P and $N_{0.25}$ are known or can be estimated. It has been shown [*Spreen*, 1947; *Burns*, 1952] that normal seasonal precipitation can be estimated quite well from topographic factors, while values of $N_{0.25}$ can be interpolated quite readily between existing stations. Hence, it is not felt that the adjusted mean daily rainfall factor limits the technique, while its inclusion materially facilitates the subsequent analysis.

Land slope—The rate of formation of precipitation is materially influenced by the rate of lifting of the air. Several indices of land slope were tested. The definition finally adopted is given by

$$\text{Land slope} = \bar{E}_{\mathrm{NE}} - \bar{E}_{\mathrm{SW}}/50 \qquad (2)$$

where $\bar{E}_{\mathrm{NE}}$ is the average elevation of the terrain in the northeast quadrant at a distance of 25 mi from the station and $\bar{E}_{\mathrm{SW}}$ is a comparable figure for the southwest quadrant. Both values were computed as the arithmetic average of seven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TRINITY
TEHAMA
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MENDOCINO
GLENN
BUTTE
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ZONES OF ENVIRONMENT

FIG. 1 – Zones of environment; the heavy dotted line marks the boundary between zones of homogeneity used by the U. S. Weather Bureau in studies of relations between rainfall intensities for various frequencies

values. The resulting slope figures are a generalized land slope in ft per mi. Data for slope (and similar parameters) were taken from U. S. Coast and Geodetic Survey aeronautical charts.

Elevation—The influence of elevation on rainfall intensity needs little discussion. Actual station elevation as reported by the U. S. Weather Bureau was used for this parameter.

Orientation—In a region where storm winds come almost exclusively from the SW quadrant, the aspect of the slope on which a station is located would be expected to be an important factor in its storm experience. Orientation was defined as the compass bearing (in degrees from *N*) of the centerline of the largest sector of a 20-mi radius circle centered at the station not containing a barrier more than 1000 ft higher than the station location.

This is a discontinuous parameter for which no regular variation in influence may be expected. Hence, stations were classified into intervals varying from 15° to 45° of orientation and inter-

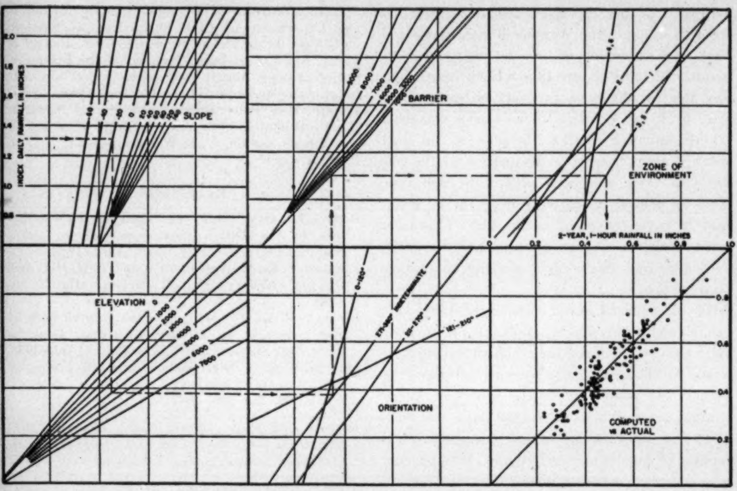

Fig. 2 – Relation between topography and rainfall intensity

polation within the curves is not appropriate. For summit stations without a barrier within 20 mi in any direction and any valley stations completely enclosed by a barrier, the orientation is designated as 'indeterminate.'

Barrier—If the air approaching a station has been forced to rise over a windward barrier, a portion of its precipitable moisture may be condensed and removed by precipitation. Hence, a barrier height was employed as a parameter. The barrier height was defined as the average of the maximum elevations within 45 mi of the station along each of seven rays from the station. The rays were in the southwest quadrant on bearings of 180°, 195°, 210°, 225°, 240°, 255°, and 270°.

Zone of environment—The first correlation developed failed to explain all of the variation in the observed rainfall intensities. Inspection of the residual errors showed some systematic geographical variations. Consequently stations were grouped into geographic zones (Fig. 1) and the zone numbers used as a final parameter. Subsequent refinements permitted combining some of the zones.

The several zones delimit natural topographic regions—mountain ranges and major valleys. This parameter undoubtedly reflects in part the greater frequency of storms in the northern part of the study area. In addition, it certainly represents a variety of topographic and climatological factors not included in the other parameters.

Results—The final relationship is shown in Figure 2. For this relation: standard error = 0.067, average error = 0.051, coefficient of correlation = 0.88, and average bias = +0.001, all based on the 126 stations employed in the analysis.

The relation is applicable to the study area previously defined but should be used with caution outside of this area.

Errors in the relationship may be expected from two causes: (1) inadequacy of the parameters utilized and (2) inadequacy of the basic data. Errors from (1) are those resulting because the selected parameters do not correctly measure the significant causal factors. Undoubtedly better parameters could be found by tedious trials but a significant gain in accuracy in unlikely. Trials in other areas would seem to offer more prospect of productive results than further work in northern California.

Errors in the basic rainfall intensity data used in the study may be quite significant. These 'errors' are not so much mistakes in recording and transcribing the raw data, as the inaccuracy of our estimates of the two-year, one-hour intensities from these data. The Weather Bureau has found that the maximum 60-min intensity averages about 1.13 times the maximum clock hour. Thus any item of the basic precipitation data might vary by 13 pct or more from the true maximum 60-min intensity. Further, because of the short record lengths there is no assurance that the true two-year event has been defined in each case. Thus an analysis based on a longer record might lead to more consistent results, that is, smaller errors. Since these errors are presumably random, such a revision might not materially change the final relation.

The relation of Figure 2 includes the index daily rainfall and thus is directly applicable for intensity estimates only where daily rainfall records are available. This, of course, permits estimates for many more points than are now served by recording gages. Where no rainfall data are available, estimates of mean annual precipitation and number of days of rain are required. It is believed that in many instances these values can be estimated more successfully than could the intensity.

Acknowledgments—This project was carried out in the Department of Civil Engineering at Stanford University under a grant from the U. S. Bureau of Public Roads. Carl Izzard represented the Bureau on project matters. Actual work on the project was done by graduate students: Herbert Osborne, David Crane, Edward Hsia, Peter Binkley, and Marcus Nomikos. Basic precipitation data were supplied by the Cooperative Studies Section, U. S. Weather Bureau, J. L. H. Paulhus, Chief.

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Some Results of Geothermal Investigations of Permafrost in Northern Alaska

MAX C. BREWER

Abstract—Frequent, regular thermal measurements in northern Alaska over a six-year period have provided information on many of the problems related to the temperature and distribution of permafrost in the Arctic. The maximum depth of permafrost near Barrow is 1330 ft. The minimum permafrost temperature recorded, below the depth of measurable (0.01° C) seasonal fluctuation (70 to 100 feet), is −10.6° C. The temperature effect of medium-sized (40 by 100 ft) heated buildings resting on permafrost is measurable to depths well below 50 ft. It is doubtful that frozen ground at shallow depths extends outward more than a few tens of feet from the shore of the Arctic Ocean although it may be present at depths greater than 100 ft. Lakes deeper than about seven feet do not freeze to bottom and may have an unfrozen zone approaching several hundred feet in depth beneath them.

Introduction—Thermal measurements made by the U. S. Geological Survey in northern Alaska for the past six years have shown that the thermal regime in permafrost areas is often predictable. (The term permafrost, as used in this report, is defined as material in which the temperature is below 0°C for two to many thousands of years in accordance with the original definition proposed by *Muller* [1947]. Surface features such as engineering structures and bodies of water produce anomalous thermal conditions in the permafrost. Topography, surface cover, and composition also affect the thermal regime of permafrost, but in this paper only areas where these factors could be held held to a minor role are described. Theoretical work on many of these relationships is progressing and will be correlated with the field data in later interpretive studies.

Techniques of observation—Temperature measurements were obtained by freezing multiconductor cables that contain regularly spaced thermistors [*Swartz*, 1954] into the ground or ice and leaving these cables in place. Readings were usually taken weekly, although they have been taken as frequently as every few hours or as infrequently as several months. The accuracy of the measurement of temperature change at any one thermistor is ±0.01°C. The accuracy for all measurements, using an ice-water bath for a standard, is believed to be better than 0.1°C.

Areas studied—The permafrost conditions in the Barrow, Cape Simpson, Umiat, and Shaviovik River areas (Fig. 1), are believed to be representative of those throughout much of northern Alaska. The engineering problems posed by the permafrost are also similar throughout these areas.

The climatological conditions at Barrow and at Umiat are assumed to be representative of the coastal plain and the interior Arctic foothills areas respectively. Barrow has an average annual air temperature of + 10.0°F (−12.2°C) (32 years of record). The freezing index (maximum cumulative degree (°F) days below freezing (32°F) for one freezing season [*Linell*, 1953]) is approximately 8600 and the thawing index (maximum cumulative degree (°F) days above freezing for one thawing season) is approximately 600. The average annual temperature at Umiat (based on six years' record) is 10.1°F (−12.1°C), the freezing index is approximately 9700 (1950–1954), and the thawing index is approximately 1650 (1950–1953). The temperature extremes at Umiat −63°F (−52.8°C) and 85°F (29.4°C) are greater than those at Barrow, −56°F (−48.9°C) and 78°F (25.6°C) largely because Umiat lacks the moderating influence of the ocean.

The Arctic coastal plain, with its many shallow lakes, usually oriented in a nearly north-south direction, is treeless and has very little local relief. The foothills province typically has a gently rolling relief of 100 to 500 ft., fewer lakes, and willows in the major stream valleys.

Depth and temperature of permafrost—The depth of permafrost in northern Alaska varies greatly depending on latitude, length of seasons, surface cover, proximity to the ocean, and the distribution of rivers and large lakes that do not freeze to the bottom.

A maximum depth of permafrost of 1330 ft is indicated eight miles south of Barrow by an extrapolation of the geothermal profile. The maximum measured depth is 1050 ft at Cape Simpson Well 13. The minimum measured depth is 820 ft at Cape Simpson Well 21 which is approx-

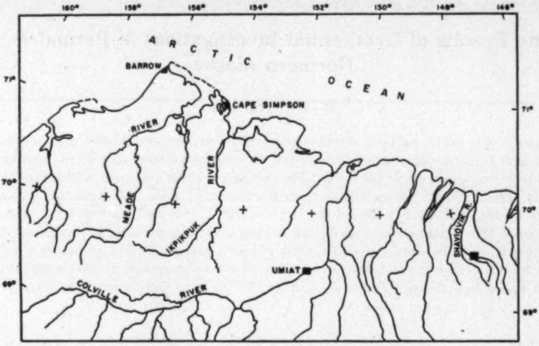

FIG. 1 – Sketch map showing selected permafrost areas studied in northern Alaska

imately 0.9 mile from the Arctic Ocean and is probably affected by the ocean and two nearby lakes.

The temperature profile for Cape Simpson Well 28 (Fig. 2), is typical of deep wells in northern Alaska. The depth of permafrost at this well is 915 ft, and the minimum temperature recorded, below the maximum depth of measurable seasonal change (70–100 feet), is −9.9°C at 140 ft. The lowest temperature recorded at similar depths in northern Alaska (near Barrow) is −10.6°C. This unusually low temperature has invariably been recorded in swampy areas of poor drainage.

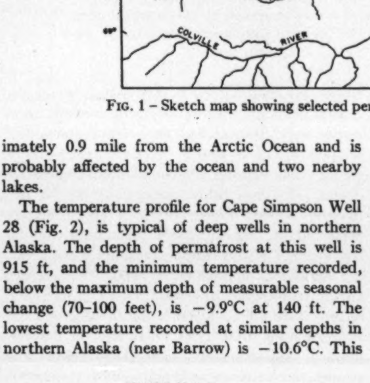

FIG. 2 – Geothermal profile for Cape Simpson Well 28, northern Alaska; data for May 22, 1953, after well had essentially returned to thermal equilibirum

The inverse temperature gradient at Simpson 28 is 74.3 ft/°C from 250 ft through the remaining thickness of permafrost and is essentially the same (74.6 feet/°C) in the 1500 ft of unfrozen sediments immediately underlying the permafrost. These inverse gradients are in the lower portion of the general range (70.4 to 135 ft/°C) of inverse gradients for similar depths in northern and central Alaska.

FACTORS MODIFYING THE TEMPERATURE OF PERMAFROST

Seasonal variations—Measurable (0.01°C) seasonal temperature fluctuations in permafrost extend to at least 70 ft in the Barrow area and may reach 100 ft.

The time-temperature curves for depths of 10, 21, 30, and 60 ft, together with a histogram of air temperatures, by five-day averages, for a typical Barrow station during the period April 1950–July 1952, (Fig. 3), are in general sinusoidal. A degree of asymmetry is noted in all curves but is more prominent at 10 and 21 feet. As the depth of measurement increases, this asymmetry dies out, and at 60 ft it is no longer noticable. The asymmetry is produced by the difference in the manner of heat passage through the active layer during the periods of thaw and freeze-up. (The active layer is ground that lies above the permafrost and thaws in the summer and freezes in the winter.)

In the spring the active layer is completely frozen. When the surface temperature starts to

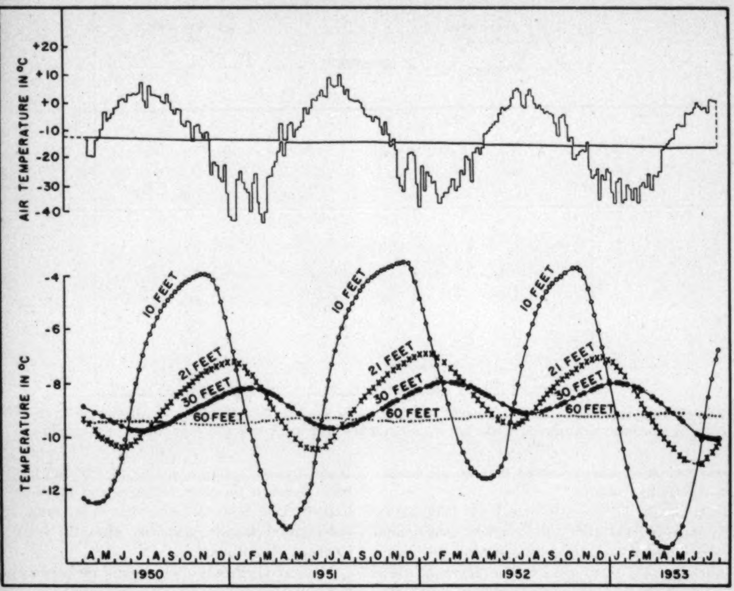

FIG. 3 – Time-temperature curves for various depths in permafrost near Barrow, Alaska, plus the corresponding air temperatures for the same period; the air temperatures are plotted using a five-day average and a datum line of −12.2°C (average annual air temperature at Barrow)

increase, the warm temperature wave gradually begins to penetrate the ground at a rate that depends on the rate of warming of the ground surface and the properties of the surface and subsurface materials. The heat and the resulting warm temperature wave can penetrate the ground for several weeks before surface melting takes place. When surface melting does take place, it does not perceptibly alter the rate of penetration of the warm temperature wave, which may have already reached a depth of 15 ft.

A different phenomenon occurs in the fall. When freezing begins at the surface, a sandwich of unfrozen ground in which the temperature is very near 0°C is caught between the downward freezing surface and the permafrost table from which a small amount of upward freezing may also be taking place, the amount depending mainly on the moisture content of the active layer material. The temperature of the permafrost just below the active layer cannot decrease as long as part of the active layer remains unfrozen (few days in sand to several weeks in wet tundra areas). Thus the cold wave may not begin to penetrate the permafrost for several weeks, the period of zero curtain. (The zero curtain is the interval of time during which the temperature remains constant as the chilling of water is temporarily compensated for by the latent heat of fusion [*Muller*, 1947].) During this period the temperatures in the shallow permafrost either rise slowly or remain constant. Once the active layer is frozen the cold temperature wave can penetrate very rapidly (Fig. 4), because the thermal gradient is very great near the surface.

As the annual temperature wave passes into the ground its amplitude diminishes and its phase is progressively retarded with increasing depth. Thus the annual temperature range in 1951–1952 (Fig. 3), decreased from 8.01°C at ten feet to 0.07°C at 60 ft and the phase of the temperature

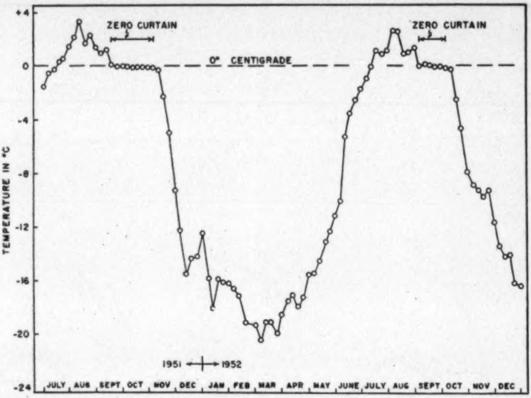

FIG. 4 – Time-temperature curve at a depth of ten inches for a tundra area near Barrow, Alaska; the curve shows a prominent 'zero curtain' in the fall of each year but little if any indication of a spring 'zero curtain'

wave at 30 ft lagged behind that at the surface by about five months.

Although the average annual air temperature at Barrow is −12.2°C, the average annual temperature at the top of permafrost often lies within the range of −7.0 to −9.5°C. The difference, which may reflect differing surface conditions including snow cover, soil-moisture content, or other physical properties, and micrometeorological conditions, is even greater in the Umiat and Fairbanks areas and points up the fact that caution should be used in interpreting permafrost temperatures strictly on the basis of air temperature data.

Heated buildings—When the floor of a heated building rests directly on or is just above (with no air circulation between the floor and the ground) ground containing permafrost, four effects are soon noted. The first and most evident is a melting of the ice wedges and other ground ice for a depth of several feet immediately beneath the building. This melting will usually cause a differential settlement of the floor of the building. The maximum settlement is often near the center of the building although the position of the point of maximum settlement can be displaced toward the location of the furnace or other heating unit. Differential settlement of as much as 20 inches within three or four years has been noted in a building at Barrow. Such differential settlement has often made it necessary to replace the floor within two or three years after heating of the building began. If the heating is stopped at a later date the thawed basin beneath the floor refreezes and the floor is heaved. One foot of heave has been noted in buildings at Barrow one year after the heating has been discontinued.

The second effect is a warming of the permafrost beneath the building. The average annual temperature may be raised by as much as 15 to 20°C just below the floors of buildings at Barrow. The increase in temperature decreases rapidly with depth (to approximately 4°C at 20 feet beneath the center of a 40 x 100-ft quonset hut after five years) but is still measurable at 50 ft. It would not be surprising if it were still measurable (greater than 0.01°C) at depths of more than 100 ft, beneath the center of a building of this size.

The third result is a damping of the amplitude of the temperature fluctuation beneath the building. This damping occurs rapidly and is very effective especially at shallow depths. A comparison of the time-temperature curve at a depth of ten feet beneath a tundra-covered area (Fig. 3) and beneath a building (Fig. 5) indicate that the damping has reduced the amplitude of the seasonal fluctuations from approximately 5°C to a few tenths of one degree C. A time lag in the rate of seasonal penetration of the warm and cold waves is still noted beneath the building.

Edge or side effects on the ground temperatures are also introduced by constructing a heated building on permafrost. These effects are noted

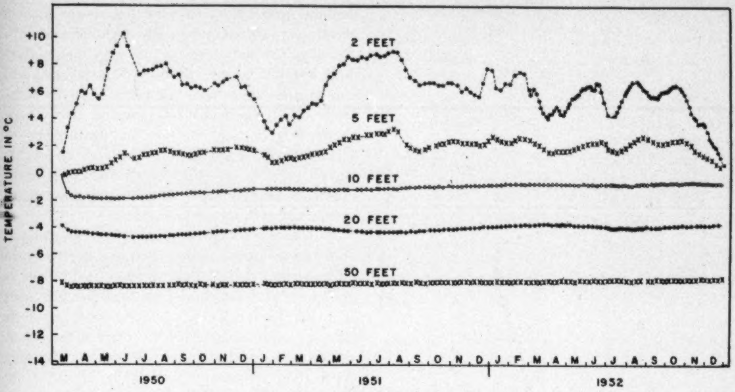

FIG. 5 – Time-temperature curves beneath a 40 × 100-ft quonset hut constructed at Barrow, Alaska, during the summer of 1947; a five-inch reinforced-concrete floor rests directly on gravel mat overlying original tundra surface

particularly in the 20-ft depth time-temperature curve, Figure 5. The side effects are shown in the form of an increased amplitude of temperature fluctuation caused by seasonal temperature changes at the 20-ft depth (also markedly shown at all depths from 16 to 32 ft) over that shown at the 10-foot depth. This fluctuation is consistent with the so-called 'hemisphere rule" which states that the edge effects on temperatures beneath the center of a building should become dominant at a depth approximately equal to one-half of the smaller dimension of the building. This rule is an empirical one based on field observations at Barrow. It has partial justification from theoretical considerations.

The effect of a heated building on the underlying permafrost temperatures shown by a comparison of temperatures in a tundra area and from beneath

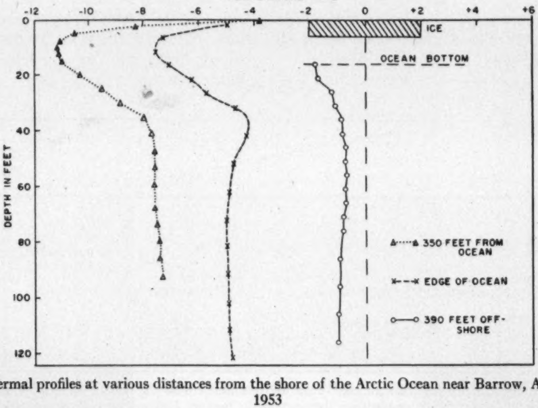

FIG. 6 – Geothermal profiles at various distances from the shore of the Arctic Ocean near Barrow, Alaska, May 21, 1953

TABLE 1 – *Temperatures at 90-ft depths near the Arctic Coast*

Location	Temperature
	°C
390 ft offshore	−0.96
edge of ocean	−4.91
350 ft onshore	−7.33

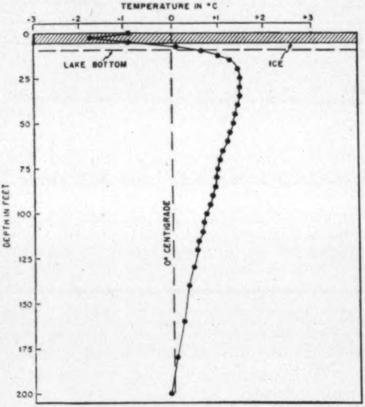

FIG. 7 – Geothermal profile beneath fresh water lake, Barrow, Alaska, May 26, 1953

a building would generally apply to any building constructed directly on permafrost in northern Alaska. The effect would be little altered by either the removal of the original tundra surface or the addition of a few inches of gravel fill. If, however, the building were placed on piles that would allow a natural air circulation beneath the building or if a forced air ventilation system) to be used in winter) were installed between the floor of the building and the ground, the underlying permafrost temperatures would be much less affected than those shown (Fig. 5), and the time-temperature curves might closely resemble those beneath an undisturbed tundra area (Fig. 3). The building would normally be safe from troubles, resulting from permafrost, with these precautions.

Proximity of the Arctic Ocean—The effect of the ocean on permafrost temperatures either becomes all important as the distance from land increases or dies out as the distance from the ocean increases (Fig. 6). The temperatures at a depth of 90 ft for various distances from the edge of the ocean on May 21, 1953 are given in Table 1. At this depth these temperatures should be affected only slightly by seasonal changes. The temperatures beneath the edge of the ocean should approximate the average of the landward and oceanward temperatures at and below 90 feet if we neglect the transient effects of a shifting shoreline and climatic variation and the thermal effect of a nearby lake (oral communication, A. H. Lachenbruch). The three temperatures given in Table 1 seem consistent with this theory.

The depth of permafrost decreases from an indicated depth of 1330 feet eight miles inland to indicated depths of 1045 feet 1200 feet from the ocean, and 670 ft, 400 ft from the ocean [*MacCarthy*, 1952]. The 1045- and 670-ft depths may be slightly modified by nearby lakes. The permafrost temperatures increase rapidly as the ocean is approached and for the first few hundred feet out under the ocean. In spite of this rapid

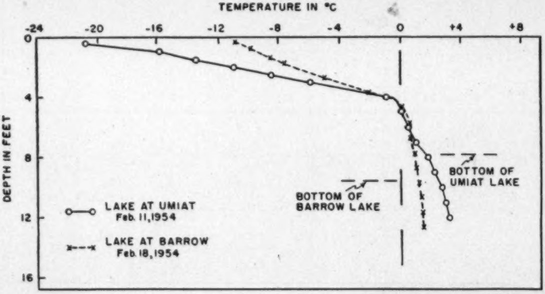

FIG. 8 – Winter thermal profiles through lakes near Barrow and Umiat (2/11/54), Alaska (Umiat data part of a cooperative project with Boston University)

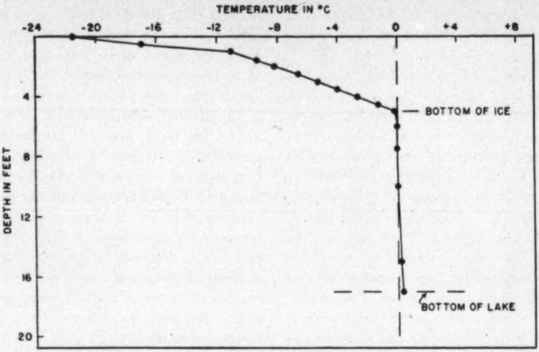

FIG. 9 – A winter thermal profile through the Colville River near Umiat, Alaska, February 19, 1954 (project conducted in part by Boston University)

increase in temperature, data from the ocean station suggest that the thickness of permafrost is still more than 400 ft at a distance of 390 ft from shore. Oceanographic investigations have shown that bottom ocean waters having a temperature below 0°C are expected until depths on the order of 500 to 1000 ft are reached. Permafrost must therefore extend seaward to ocean depths of 500 to 1000 ft.

If the formations beneath the ocean site 390 ft from shore contain fresh water, it appears from the graph that they would be frozen. If the formations contain sea water, they are definitely not frozen. Because a concentrated brine is found at depths of from 10 to 160 ft on land near shore and because sea water overlies these formations, it has been tentatively concluded that frozen ground does not exist beneath the ocean floor for more than a few hundred feet offshore. The driller's log for the hole indicated no frozen material to 100 ft, the possibility of frozen ground from 100 to 205 ft, and the possible existence of unfrozen layers (referred to as taliks in Russian) from 205 to 326 ft. By definition, however, the formations throughout all but the top few feet penetrated by the hole are in permafrost.

Shallow lakes and rivers—Much of the land surface of the Alaskan Arctic coastal plain is covered by shallow lakes. The lake basins in the Barrow area, seem to fall into two general depth ranges, either two to three feet or six to nine feet. In lakes two to three feet deep the thaw will penetrate to the bottom of the lake and commonly into the sediments from a few inches to possibly two feet during the summer. This active layer becomes frozen by midwinter. The permafrost temperatures at depth under these lakes are higher than those under the surrounding tundra, usually on the order of 0° to 3°C depending on the size and depth of the lake.

Lakes six to nine feet deep do not freeze to the bottom. The depth of the unfrozen basin beneath varies according to the size of the lake, depth and size of the six- to nine-foot part, and the long-term

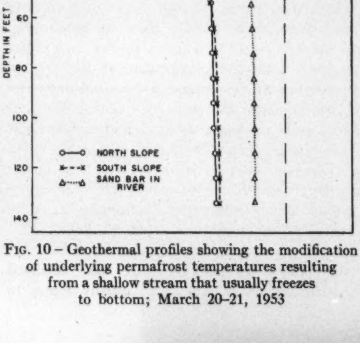

FIG. 10 – Geothermal profiles showing the modification of underlying permafrost temperatures resulting from a shallow stream that usually freezes to bottom; March 20–21, 1953

average annual temperature of the water. The geothermal profile beneath a fresh water lake six to nine feet deep and approximately 2500 ft in diameter is shown in Figure 7. This profile was taken in late winter when the ice was thickest, about six feet, and the water was only three feet deep. The temperature of the water ranged from 0.5 to 1.0°C. The depth to permafrost under this part of the lake is 190 ft, although the permafrost may actually be unfrozen to greater depths because of the possibility of a high brine content in the formations. The temperature profile beneath this lake (Fig. 7) would continue to show decreasing temperatures to some depth where a minimum would be reached. Below this depth, the temperature profile would be expected to show a thermal gradient approaching that common to the surrounding area at similar depths.

A comparison (Fig. 8) of the thermal regimes of a lake at Barrow on the coastal plain and a lake at Umiat in the foothills indicates that both lakes have unfrozen basins beneath them. However, the temperatures of the bottom sediments in the Umiat lake are approximately 2°C higher than those at Barrow. The difference is approximately the same as that noted in permafrost temperatures in the two areas. The differences in permafrost temperatures can be traced to the differences in average annual near-surface ground temperatures. The longer ice-free period at Umiat also contributes to the higher lake-bottom temperatures in that area. The differences in the lake-bottom temperatures at Barrow and Umiat as well as the differences in permafrost temperatures between the two places illustrates the risk involved in the indiscriminate use of average annual air temperatures to predict ground temperatures because Barrow and Umiat have almost identical average annual air temperatures.

A thermal profile through the ice and water to the bottom of the Colville River at Umiat (Fig. 9) is nearly vertical beneath the ice and differs markedly from the lake profiles at Barrow and Umiat (Fig. 8). One explanation for this difference is that the lakes are relatively stagnant in winter and a more moderate thermal gradient develops. The mixing caused by turbulence in the river water prevents the development of a similar gradient beneath the river ice. This turbulence also accounts for the heavy concentration of ice crystals in the water (to a depth of 12 ft in 1953) beneath the river ice in early fall.

Permafrost temperatures are also modified beneath shallow streams that usually freeze to bottom (Fig. 10). One hole was drilled on a small sand bar in the middle of the west fork of the Shaviovik River. Holes were also drilled a quarter of a mile on either side of the hole on the sand bar in the river. The data from all three holes were obtained soon after they were drilled, using air as the fluid, and the temperatures had not completely returned to equilibrium. However, they indicate that the river has introduced approximately 3°C of warming into the permafrost to a depth of 135 ft. Barring any other permafrost temperature modifications these profiles would be expected to converge at greater depths.

From these results and other data, it seems reasonable to make the following general remarks about lakes and rivers in northern Alaska: (1) In this region of the Arctic, lakes having a diameter of approximately one-half mile or more and a depth of at least seven feet may be expected to have unfrozen basins beneath them to a depth of 200 ft or more. (2) Should these lakes be underlain by sands or gravels of favorable water-bearing characteristics they could provide a limited and probably not immediately replenishable winter water supply. (3) Should these lakes lie within five miles of the Arctic Coast the underlying formations may contain saline rather than fresh water. (4) The best year-around fresh-water source in the Arctic is an uncontaminated lake or stream, provided that the minimum depth at some part of the body of water is at least seven or eight feet.

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Acknowledgment is also extended to the Boston University Keys Project personnel for assistance in obtaining data presented in Figures 8 and 9.

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A Method for the Measurement of Absolute Gravity

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Abstract—The greatest difficulty in measurements of absolute gravity with either pendulums or falling bodies is the distance determination. It is proposed to avoid the distance measurement in a falling-body experiment by determining g in terms of c, the velocity of light. A pulse of light is directed up toward and reflected from a falling ball. The reflected light pulse, upon being detected by a photomultiplier, initiates a new pulse. A pulse recycle oscillator is thus set up whose frequency is a function of the position of the ball. By measuring the frequency for three successive time intervals, g may be determined in units of c independent of the time and position at the release of the ball.

Introduction—The precise determination of the acceleration of gravity has long been a problem of scientific importance, and despite many painstaking experiments involving years of work there is still an apparent uncertainty of about five milligals (0.005 cm/sec^2) in the best measurements and about 12 mgal in the international datum value adopted for relative gravity measurements. Since the gravitational unit is fundamental to many other measurements, and the above inaccuracies constitute a limiting factor in many experiments, there is a definite need for a method that will permit the reliable determination of g to 1 mgal or better. As *Silsbee* [1956] has stated, knowledge of the absolute value of g is an essential link in at least two fundamental measurements of physics. The unit of electric current, the ampere, is defined in terms of the force developed between two current-carrying conductors in a specified geometrical configuration. By far the most convenient method for measuring this force is to balance it against the weight, mg, of a known mass m. It is from the ampere thus determined that other units, such as the watt, joule, oersted, and gauss, are derived. The other measurement is to use g in determining the force on a conductor while it is carrying a known current in a magnetic field. This, when combined with the measured resonance frequency of protons when in that field, yields the gyromagnetic ratio of the proton, one of the very fundamental atomic constants.

With the advent of the International Geophysical Year and the international gravity and satellite programs, the need for a more precise determination of g is brought into prominence on several problems. Some of these are the adoption of a standard international gravitational unit, the coordination and integration of the world's gravity data, the determination of the undulations of the geoid, the geoidal positions of the continents, and the shape of the Earth. From the orbital configuration and motions of the IGY satellites it should be possible also to determine independently, to a higher degree of accuracy than hitherto, the degree of polar flattening of the Earth and the product of the mass of the Earth with the gravitational constant. These measurements, coupled with a more precise value of g would permit a revision of several fundamental geophysical constants.

Methods of investigation that have been used for determining g—To determine absolute gravity there are two fundamental methods, one based on the period of a freely oscillating pendulum and the other on changes in velocity of a freely falling body.

Pendulum methods can be recorded very easily, but require precise measurement of both length and time as well as a flexure correction for the pendulum to one part in a million to obtain an accuracy of one milligal. An associated problem is the change in length of the pendulum when suspended on its knife edges. For a one meter pendulum, the length increase for suspension by its upper end is about one part in a million, which must be measured and corrected. This is difficult. If the pendulum is made longer, it becomes easier to measure the elongation, but the increase in mass exerts more force on the support and the pendulum is subject to greater flexure. The amount of flexure is very difficult to measure and the effects hard to evaluate. The most precise pendulum observations yet made, those at the Potsdam Geodetic Institute in Germany (Revised Potsdam value, by Harold Jeffreys based on different flexure corrections from those originally used, which gave a disagreement of over 12 mgals with other sites), the National Physical Laboratory at Teddington, England, and the National Bureau of Standards in Washington, D. C. have a standard deviation of six milligals for absolute g when intercompared on a relative gravity basis. While pendulums are again being used for the present measurements in Buenos Aires, Argentina, there appears to be fairly general agreement that the pendulum method can not determine absolute g with a reliability of one milligal and probably no more than three to four mgals.

The other classical mechanics scheme used to determine absolute g is to measure the velocity changes of a freely falling body. Most of the free-fall methods have employed some sort of rod for the falling body. While the rod can be accurately scribed with distance marks, there are longitudinal rod oscillations resulting from release of the rod which are difficult to measure. As the enclosing tube probably oscillates as a consequence of releasing the rod, this means that the rod and recording device could oscillate out of phase with each other. Because the amplitude of this oscillation is on the order of 10^{-6} of the length of the rod, there is a resulting uncertainty of one or two milligals that is inherent in the method assuming that recording presents no significant problem, which it does. The observations have been difficult, expensive, and not altogether satisfactory, as evidenced by the experience of Volet in France over the past ten years and that of the National Research Council group in Canada over the past seven years.

In summary, the methods tried to date all have been severely handicapped by mechanical difficulties, in part related to the measurement of length and flexure and in part related to the one-shot spot-sampling methods of recording. These limitations have resulted in errors that are extremely difficult to evaluate and led to uncertainties in the determination of g of the order of several milligals.

In order to get a more accurate determination of g, it is felt that an entirely different experiment and procedure is required; one that will circumvent the difficulties attendant upon the methods described. It is believed that this can be achieved by dropping a ball rather than a rod and by using the velocity of light as a standard of measurement for determining the change in rate of fall. While the idea of dropping a ball rather than a rod is not new, the idea of using the velocity of light as a means of determining the change in rate of fall is believed to be new and the significant departure from the previous techniques tried. (E. C. Bullard in personal conversation with G. P. Woollard proposed a few years ago a measurement of g whereby a ball would be flipped by a spring vertically upward and its change in velocity noted both on the rise and fall from the point of maximum rise.)

General considerations and proposed method—According to *Eddington* [1949] the standard of of length must be a quantum specified structure. Eddington shows that the unique quantum specified metric is the same as the σ metric where σ is the local uncertainty of position in a given direction, that is, the standard deviation of the mean value of a wave packet. It is then possible to show that the use of the wave length of the H_α line is equivalent to using the σ metric. Therefore, the unit of length may be taken as the wave length of the H_α line (or some other quantum specified wave length). The standard of time is likewise defined by the period of light waves. The ratio of the wave length to the period of H_α light is the velocity of light, and this quantity must be constant for all places and times. Since the velocity of light is a ratio of the fundamental units of length and time, it follows that it is a fundamental unit of velocity.

It should, therefore, be possible to measure g in terms of the standard velocity c, the velocity of light. The expression for g is then in terms of c divided by time and there is no need to express or to measure lengths in any other units. The final expression for g will be in terms of units just as fundamental as any others that might be used. The units will be more fundamental and more truly standard than those usually expressed, namely, units based on the standard meter.

The velocity of light is known now to an accuracy of about one part in a million, and the system of equations which follow give g in terms of c. With a better value for the velocity of light, and a timing accuracy of 10^{-8} sec, g could be obtained to 0.1 mgal with the method proposed. It also should be possible to measure the velocity of light in the evacuated tube by setting up a half-silvered mirror system where the distance between mirrors could be measured with an interferometer.

It is also worth mentioning that balls of different masses can be dropped, permitting a test of the fundamental Einstein postulate of the equivalence of inertial and gravitational mass to a six-place accuracy.

Because of the small and symmetric nature of a dropped ball, and because it is expendable, many other variations of the proposed experiment are possible. Some of these are: (1) dropping electrically charged or magnetized balls (of course external fields could be shielded as desired), and (2) application of external electric and/or magnetic fields.

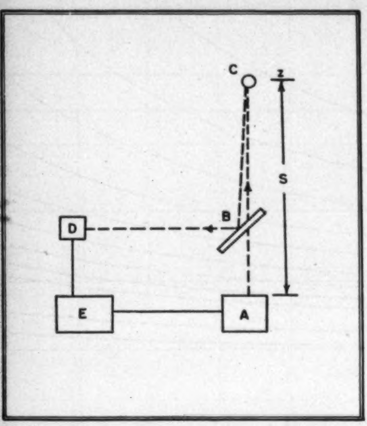

FIG. 1 – Schematic drawing of proposed experiment; A, light pulser; B, half-silvered mirror; C, falling ball; D, photomultiplier; E, pulse forming circuit

Proposed experiment—The following experiment is proposed. A spherical body is dropped from a position taken as the origin of the coordinate axes and falls in the positive z-direction starting from rest at time $t = 0$. At a time t

$$z = \tfrac{1}{2}gt^2 \tag{1}$$

where $z = 0$ at time $t = 0$.

The distance measurement is eliminated by using pulses of light to determine the instantaneous position of the body. The procedure would be to send a pulse of light up to the freely falling spherical body. The light pulse is reflected from the bottom surface of the body to a light sensitive device adjacent to the light pulser. When the reflected light pulse is detected it initiates a new pulse from the source. The light source may be modulated electronically by some means, as the Kerr effect. The pulses may be detected by a suitable light detecting device, such as a photomultiplier tube, as shown schematically in Figure 1.

Theoretical development—Let S be the distance from the source to the ball at time t and also the distance from the ball to the photocathode of the photomultiplier. Let S_0 be the distance from the Kerr cell or photomultiplier to the plane $z = 0$ (the release point). At some time t after the ball is released a pulse of light is sent out from the Kerr cell, travels distance S to the ball and then reflects back distance S to the photomultiplier. The resulting output pulse of the multiplier is fed through a pulse-forming circuit generating a new pulse from the Kerr cell. As each succeeding pulse is received by the multiplier, it generates the next light source pulse.

Let τ_1 = time delay in the photomultiplier tube
τ_2 = time delay in intervening pulsing circuits
τ_3 = time delay in the Kerr cell

Since τ_1, τ_2, τ_3 are constants, let

$$T_0 = \tau_1 + \tau_2 + \tau_3 \tag{2}$$

At any instantaneous time t the time of travel of the light pulse from the light source to the ball and back to the photocathode will be

$$\Delta t = 2S/c \tag{3}$$

where c = velocity of light; the instantaneous frequency ν for one complete cycle will be

$$\nu = 1/(\Delta t + T_0) = c/(2S + cT_0) \tag{4}$$

Since

$$S = S_0 - z \tag{5}$$

it follows from (1)

$$\nu = c/[(2S_0 + cT_0) - gt^2] \tag{6}$$

Letting

$$K = 2S_0 + cT_0 \tag{7}$$

(6 becomes)

$$\nu = c/g(K/g - t^2) \tag{8}$$

Integration between times t_1 and t_2 for $t_2 > t_1 > 0$ gives

$$N_1 = \int_{t_1}^{t_2} \nu\, dt = \frac{c}{g}\int_{t_1}^{t_2} \frac{1}{(K/g - t^2)}\, dt$$

$$= \frac{cg^{-\frac{1}{2}}}{2\sqrt{K}} \ln \frac{\sqrt{K/g} + t}{\sqrt{K/g} - t}\bigg|_{t_1}^{t_2} \tag{9}$$

or

$$N_1 = \frac{cg^{-\frac{1}{2}}}{2\sqrt{K}} \ln \frac{(\sqrt{K/g} + t_2)(\sqrt{K/g} - t_1)}{(\sqrt{K/g} - t_2)(\sqrt{K/g} + t_1)} \tag{10a}$$

where N_1 is the number of cycles or events in the time interval $t_2 - t_1$. Similarly for time intervals $t_3 - t_2$ and $t_4 - t_3$ we obtain the result

$$N_2 = \frac{cg^{-\frac{1}{2}}}{2\sqrt{K}} \ln \frac{(\sqrt{K/g} + t_3)(\sqrt{K/g} - t_2)}{(\sqrt{K/g} - t_3)(\sqrt{K/g} + t_2)} \tag{10b}$$

$$N_3 = \frac{cg^{-\frac{1}{2}}}{2\sqrt{K}} \ln \frac{(\sqrt{K/g} + t_4)(\sqrt{K/g} - t_3)}{(\sqrt{K/g} - t_4)(\sqrt{K/g} + t_3)} \tag{10c}$$

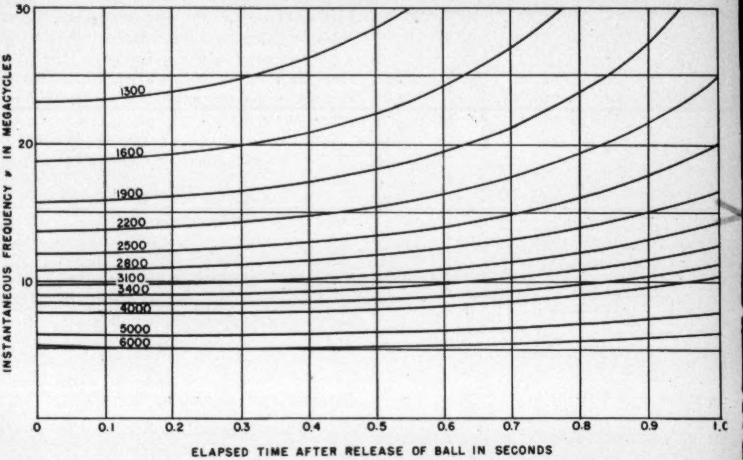

FIG. 2 – Instantaneous frequency versus elapsed time after release of ball for values of K from 1300 to 6000; $\nu = c/(K - gt^2)$

This gives a set of three equations with three unknowns g, K, and t_1. Since the equations are non-linear, it is necessary to use numerical approximation methods for their solutions. Among the methods which can be used, the Newton-Raphson method seems to work well and can easily be applied. Solution is adaptable to the use of an electronic digital computer, such as the IBM model 650.

Sensitivity considerations of falling-ball experiment—The pulse recycle frequency for light pulses reflected from a falling ball is

$$\nu = c/(K - gt^2) \tag{11}$$

where $K = 2S_0 + cT_0$
t = time after start of ball drop in seconds
S_0 = distance in cm from the light-source detector to the ball at time $t = 0$
T_0 = delay time in electronic circuits in sec
c = velocity of light in cm/sec
g = value of gravitational acceleration in gals

Figure 2 shows plots of the family of frequency curves for different values of K. Figure 3 gives the possible values of S_0 and T_0 for each K plotted in Figure 2.

The experimental procedure would be to count the number of recycle pulses in a time interval $(t_2 - t_1)$ where $t_2 > t_1 > 0$. To measure g independent of the initial conditions, it is required to measure the number of counts over three different time intervals. The number of counts in $(t_2 - t_1)$ is

$$N = \int_{t_1}^{t_2} \nu \, dt \tag{12}$$

The sensitivity is the change in number of counts per change in g or

$$dN/dg = (d/dg) \int_{t_1}^{t_2} \nu \, dt = \int_{t_1}^{t_2} (d\nu/dg) \, dt \tag{13}$$

where differentiation under the integral sign is permitted since the integration is independent of g.

Now $d\nu/dg = ct^2/(K - gt^2)^2$

$$\therefore dN/dg = \int_{t_1}^{t_2} [ct^2/(K - gt^2)^2] \, dt \tag{13a}$$

Upon integrating by parts

$$dN/dg = ct/2g(K - gt^2) \Big|_{t_1}^{t_2} - \int_{t_1}^{t_2} c \, dt/2g(K - gt^2) \tag{13b}$$

Substituting in the value of ν given in (11)

$$dN/dg = (1/2g)[t_2\nu_2 - t_1\nu_1 - N] \tag{14}$$

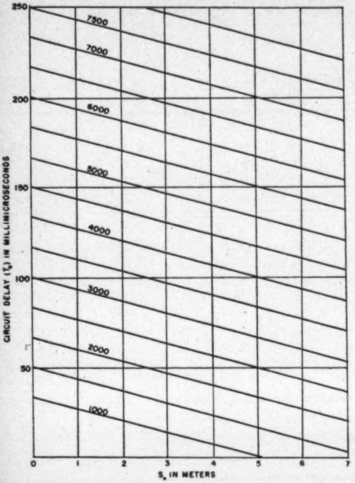

FIG. 3 – Circuit delay time T_0 versus drop height S_0 for values of K from 1000 to 8000; $K = 2S_0 + cT_0$

where ν_2 and ν_2 are the frequencies at times t_1 and t_2 respectively. From the plot of the relationship of ν to t (Fig. 4) it is possible to express Equation (14) in a more convenient form. Comparing (14) with Figure 4, it is seen that

$$2g\, dN/dg = \text{shaded area}$$

since $\nu_2 t_2$ and $\nu_1 t_1$ represent rectangular areas and N represents the area under the curve between t_2 and t_1, by (2).

$$\text{The shaded area} = \int_{\nu_1}^{\nu_2} t\, d\nu = \int_{t_1}^{t_2} t(d\nu/dt)\, dt$$

For small values of $t_2 - t_1 = \Delta t$

$$dN/dg = (1/2g)\ (t(d\nu/dt)\Delta t)$$

From (11) $d\nu/dt = 2cgt/(K - gt^2)^2$

$$\therefore dN/dg = [ct^3/(K - gt^2)^2]\Delta t \qquad (15)$$

This expression gives the sensitivity in counts per gal in terms of t, K, and Δt when the latter are given in cgs units. Table 1 gives values of the sensitivity in counts per milligal for different experimental parameters as calculated from (15). The sensitivities are given for the first of three equal intervals of time of $\Delta t = 0.1$ sec.

This is thus the minimum sensitivity because the latter two intervals having larger values of t will have higher values of dN/dg. The value of t was chosen at the center of each 0.1 sec time interval and the resultant error in dN/dg due to the finite value of Δt is not more than a few per cent; this is quite sufficient to allow a choice of parameters to get an adequate sensitivity. S_0 is the distance from the drop point to 50 cm beyond the last of the three counting intervals. The 50 cm at the bottom allows time and space to deflect the ball at the end of its fall. R is the height at which counting actually begins. Even in cases where a long tube is needed to drop the ball, the light-reflection problem is not great as the recording of data is only done during the last part of the fall. Little sensitivity is gained by recording the initial part of the fall, that is, when t is small. There are two advantages in recording over a shorter time toward the end of the fall: (1) a shorter light path to the ball during recording, and (2) a narrower band width of frequencies. It also should be mentioned that if the ball is given an initial velocity, the tube length need only be a little longer than R_1, thus improving portability.

In Table 1 the sensitivity calculated for each corresponding pulse recycle frequency range is given along with the requirements of tube height, delay time and counting accuracy to obtain results accurate to 1 mgal. It is felt that the delay times of Table 1 are quite realistic. $T_0 = 10^{-7}$ sec should be easily attainable and 5×10^{-8} can probably be reached with a little refinement. A photomultiplier tube like the RCA 6810 has a delay of from 2 to 3 $\times\ 10^{-8}$ sec. The transit time through the light source will be 1 or 2×10^{-8} sec. Pulse shapers and amplifiers will account for the remainder of T_0. A typical pulse amplifier as the Hewlett Packard

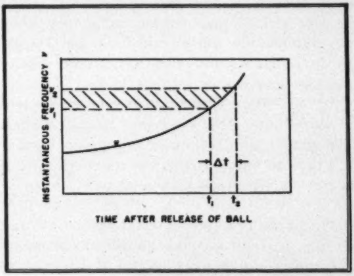

FIG. 4 – Instantaneous frequency (ν) as a function of time after release of the ball

TABLE 1 – *Minimum sensitivity at different dropping heights for three different delay times*

Dropping height S_0	Maximum recording height R[a]	$T_0 = 10 \times 10^{-8}$ sec		$T_0 = 8 \times 10^{-8}$ sec		$T_0 = 5 \times 10^{-8}$ sec	
		Sensitivity[b] in counts per milligal; $(dN/dg) \times 10^{-3}$	Band width	Sensitivity[b] in counts per milligal; $(dN/dg) \times 10^{-3}$	Band width	Sensitivity[b] in counts per milligal; $(dN/dg) \times 10^{-3}$	Band width
cm	cm		mc		mc		mc
230	185	0.033	8.9–9.7	0.049	10.8–12	0.108	16.0–18.8
295	215	0.053	8.7–9.7	0.078	10.6–12	0.171	15.6–18.8
370	245	0.077	8.6–9.7	0.112	10.4–12	0.241	15.1–18.8
455	275	0.104	8.4–9.7	0.151	10.1–12	0.321	14.6–18.8
550	305	0.135	8.3–9.7	0.195	9.9–12	0.406	14.2–18.8
655	335	0.170	8.1–9.7	0.243	9.7–12	0.497	13.8–18.8
770	365	0.205	8.0–9.7	0.293	9.6–12	0.592	13.4–18.8
895	395	0.243	7.9–9.7	0.346	9.4–12	0.688	13.1–18.8
1030	425	0.283	7.7–9.7	0.402	9.2–12	0.790	12.7–18.8
1175	455	0.327	7.6–9.7	0.461	9.0–12	0.895	12.4–18.8
1330	485	0.371	7.5–9.7	0.521	8.9–12	1.090	12.1–18.8
1495	515	0.417	7.4–9.7	0.583	8.7–12	1.105	11.8–18.8

Pulses are counted during 0.3 sec of fall. The ball is 50 cm from the bottom of the tube at the end of counting.

[a] R is the height at which counting began.

[b] Sensitivity is for the first 0.1 sec interval of 3 intervals counted.

460AR has a delay of 1.4×10^{-8} sec. A delay of 8×10^{-8} is thus possible with presently available components. New types of photomultiplier tubes such as the transmission type multiplier now in development at Westinghouse promise to give a shorter transit time than the RCA 6810.

The proposed method of counting pulses is to display pulses as modulation dots on an oscilloscope trace. The traces will be modulated to give a raster of traces as on a television screen. A TV monitor will resolve as many as 500 lines, both vertically and horizontally. This will allow as many as a fourth of a million dots on one tube face. The total number of pulses in a run would be from 3–6 million. But it is not necessary to display every pulse on the screen. Suppose the intensity of the dots is varied so that every tenth dot is brighter, every hundredth is brighter still, etc. This could be done with a beam switching tube which when run continuously will operate to 20 mc. The intensity coding will thus allow a good proportion of the dots to be left out.

An oscilloscope with a fast sweep could be used to spread dots to one centimeter apart or greater. Timing marks in the form of fast rise time pulses will then be introduced on the traces from a frequency standard such as those made by Hycon or Knights, which are stable to one part in 10^{-9}. With fast rise times on both pulse recycle dots and on time marks, it should be possible to determine the number of pulses per interval of time to $\frac{1}{10}$ of a pulse or better at frequencies below 20 mc. The scope traces can be photographed using standard oscilloscope trace photographing techniques. This has the advantage of producing a clear and permanent record of results.

Size of apparatus—From Table 1 a typical example of instrument parameters would be $S_0 = 655$ cm or about a 22 ft tube. The maximum height of the ball during recording would be 335 cm or about 11 ft. At $T_0 = 8 \times 10^{-8}$ sec the minimum sensitivity is about $\frac{1}{4}$ count so that a determination of $\frac{1}{10}$ count would allow a g determination of ±0.5 mgal. The frequencies would be from 9.7–12 mc.

It is therefore apparent that with a reasonable size drop tube and light path with a delay time in the electronics of 8×10^{-8} seconds, a result accurate to at least one milligal is possible.

Static stability evaluations—Starting with the expression for the frequency

$$\nu = c/(K - gt^2) = ct^2/(K/t^2 - g)$$

$$K = 2S_0 + cT_0$$

it is seen that a change in g of one milligal will be equivalent to a change in K/t^2 of 10^{-3} gals. Consider the case where $S_0 = 655$ cm, $t = 0.85$ sec, and $T_0 = 8 \times 10^{-8}$ sec which gives sufficient sensitivity. Then

$$K/t^2 = 10^{-3} \text{ gals}$$

$$K = 0.722 \times 10^{-3} \text{ cm}$$

$$S_0 = 0.361 \times 10^{-3} \text{ cm}$$

Thus a change of 3.61×10^{-4} cm between the ball and the source will produce an error of one milligal. Note this is calculated at $t = 0.85$ sec or at the same instant for which the sensitivity of 0.24 counts/mgal was calculated in Table 1. The change in distance can occur either at the ball or at the source detection end. The changes in ball size during the 0.3 sec of recording will be negligible. For steel the temperature coefficient of expansion is 10^{-5} per degree C. The change in shape of a one-centimeter radius steel ball due to deformation caused by the force of its own mass would be about 10^{-8} cm. The base upon which the recording unit sits would have to remain stable to 3.61×10^{-4} cm for 0.3 sec. It does not appear that temperature changes over this short a time will be significant. Vibrations caused by seismic activity or other sources might well cause some error. However, these may be monitored and drops made when conditions are quiet. It might be mentioned that in the Michelson-Morley experiment static stability of 6×10^{-7} cm had to be maintained.

As the ball drops, the radius of the spherical wave front at the photomultiplier face decreases. This will produce an error due to a change in rise time of the signal input. Using the values 50 cm and 355 cm as the limits of the ball's distance during recording, the difference in curvature of the wave front will produce a rise time error equivalent to a displacement of 3.4×10^{-3} cm. This is equivalent to about 100 mgals. Though optical methods of compensation could be used, it is felt that it would be simpler to correct for the error. Static tests could easily evaluate the effect to better than one per cent, which would be sufficient to get one-milligal accuracy. It should be added that other effects dependent upon the distance of the ball from the source such as variation in light intensity might be corrected for by running static tests and actually calibrating to determine the error introduced.

Portability of the equipment—The sensitivity of the experiment increases as the velocity of the ball increases. The obvious way of getting high initial velocity during the recording time interval is to drop the ball through a greater path length. With increased sensitivity a smaller recording time interval may be used. The result is that regardless of the total path length, the recording is done only during the time the ball is within two or three meters of the pulsing and pick-up devices. This suggests that the drop tube need not be any more than three meters in length provided that some small precise spring device at the top "shoots" the ball downard. In fact, portability of the tube is no great problem even if it were long since it could be made in sections that fit together with O-ring vacuum seals. The pulser and pick-up devices do not need to be in the vacuum, that is, the bottom of the tube can be terminated with a piece of plate glass. The intervening air space between glass and transducer would act as a short time delay filter, easily constant during the 0.3 sec duration of the recording.

Preliminary experimental tests—The first phase of the experiment now in progress is to set up a recycle light oscillator and test for frequency stability. The requirements for this are a light source capable of 10 – 20-mc modulation, a high sensitivity, fast photomultiplier, and the intermediate pulse shaping and amplifying circuitry. In this initial stage of the experiment static tests of frequency stability are being made by choosing a light path distance such that the pulse recycle frequency is close to the carrier frequency of WWV. The stability of the pulse recycle frequency is governed by the stability of the electron transit times in the electronic circuitry. Since the electron transit time in a vacuum tube varies as the square root of the applied potential, a gravity result accurate to one milligal will require a voltage stability of one part in one million.

Conclusions—The proposed falling-ball method is essentially a continuum experiment, with the advantages that no direct distance measurement is involved, and that mechanical oscillations of the falling ball (if any) caused by release, would be readily observable as cyclic low frequency variations superimposed on the high recycle frequency. The high recycle frequency changes smoothly and uniformly with time. The chief advantage of the method is that for the first time absolute g would be given in terms of a fundamental and universal quantity, the velocity of light. A relatively simple conversion of the gravity method will also permit a precise direct measurement of the velocity of light in a vacuum.

Disadvantages of the falling-ball method are believed to be entirely electronic rather than mechanical. Problems related to geometrical optics such as change in curvature of the wave front arriving at the photomultiplier can be evaluated by static measurements, and corrected. Variable electronic delay time can be partially controlled by use of precise potentials on all vacuum tube devices. Static tests are easy to perform, and the transit time must be stable for only 0.3 sec.

All of the current methods are decidedly not portable and are subject to mechanical as well as electronic problems. The proposed method is felt to have a distinct recommendation in that it can be made portable and *g* can be measured in terms of a universal constant. The problems are principally electronic in nature and can either be circumvented or corrected for. In principle the experiment is capable of yielding 0.1 milligal accuracy. In addition, the method is easily adaptable to tests related to the fundamental nature of gravitation.

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Least Squares in Magnetic and Gravity Interpretation

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Abstract—Methods of applying least squares to profiles of magnetic intensity over polarized bodies to obtain the parameters of the anomaly equations are developed, and examples of calculations are given. It is shown that the method is also directly applicable to gravity.

Introduction—In exploration geophysics, as in all the exact sciences, fitting equations of various kinds to observed values is one of the essential operations in treating the data. Magnetic interpretation is no exception, especially in its final stage, when the anomaly field is explained in terms of geological structure. Equations giving the theoretical effects of various bodies, taken to represent geological conditions, are fitted to the observed effects in an attempt to discover the body giving the best representation, and so evaluate parameters giving its position, size, and magnetic properties.

In its simplest form, when profiles are taken across the bodies, interpretation involves fitting to two-dimensional curves. It is this particular form of the problem to which we will confine ourselves here.

One method of solution involves locating critical, inflection, half-maximum and other points, and calculating the parameters from these [*Nettleton*, 1940, p. 224; *Heiland*, 1946, pp. 381–389; *Smellie*, 1956]. The theoretical curve is then plotted and compared to the observed one, and, as is usually necessary, the parameters are readjusted and the curves replotted until a better fit is obtained.

However, any method requiring the judgment of the interpreter at intermediate stages of the calculation has many disadvantages. Especially when calculations can be programmed for the electronic computer, it is desirable to have other methods available, whereby a fit can be systematically determined.

Least squares is such a method. The chief difficulty in its application is that an algebraic solution for the parameters cannot usually be obtained if the equations are not linear. This is usually the case for the equations of magnetic interpretation.

It is the purpose of this paper to examine these equations, with the view of utilizing certain of their properties in obtaining numerical or other indirect solutions for the parameters.

The form of the magnetic equations—The magnetic potential U_p at a point P, due to a body with uniform intensity of magnetization I along the axis s is given [*Jeans*, 1948, p. 375] by

$$U_p = I \frac{\partial}{\partial s} \iiint \frac{dV}{r} \tag{1}$$

where dV is an elementary volume, r is the distance from the element to the observer, and integration is over the body.

The observed quantity is usually magnetic intensity; that is, the derivative of U_p in some chosen direction. Let V represent this quantity. Considering (1), it is apparent that if axes are chosen with the z-axis vertically downward, and if the observer traverses the x-axis

$$V = k\, F(x, d_j) \tag{2}$$

where $k = cI$, c and the d_j being a number of parameters giving the size and position of the body, as well as the direction of magnetization and the direction of measurement.

Let us now examine the application of the theory of least squares in obtaining a best fit of (2) to a number of observed values of V.

Applying least squares to the magnetic equations—By the theory of least squares [*Reddick* and *Miller*, 1938, pp. 345–349], the best fit of a function $y(x)$ to a number of observed values $y_1, y_2, \cdots$ is attained when $S = \sum_i [y_i - y(x_i)]^2$ is a minimum; that is, when the derivatives of S with respect to all the parameters of $y(x)$ are simultaneously zero. Applying this theory to (2), we have

$$S = \sum_i [Vi - kF(x_i, dj)]^2 \tag{3}$$

V_i being the observed values of V at the points x_i, and the conditions for minimal S are

$$\frac{\partial S}{\partial I} = \sum_i 2cF(x_i, d_j)[V_i - kF(x_i, d_j)] = 0 \tag{4}$$

$$\frac{\partial S}{\partial c} = \sum_i 2IF(x_i, d_j)[V_i - kF(x_i, d_j)] = 0 \tag{5}$$

$$\frac{\partial S}{\partial d_l} = \sum_i 2k[V_i - kF(x_i, d_j)] \frac{\partial F(x_i, d_j)}{\partial d_l} = 0 \tag{6}$$

d_l being representative of the d_j. These reduce to

$$\sum_i V_i F(x_i, d_j) - k \sum F^2(x_i, d_j) = 0 \qquad (7)$$

$$\sum_i V_i \frac{\partial F(x_i, d_j)}{\partial d_l} - k \sum_i F(x_i, d_j) \frac{\partial F(x_i, d_j)}{\partial d_l} = 0 \qquad (8)$$

Methods of solving (7) *and* (8)—When $F(x_i, d_j)$ can be expressed in terms of functions of x_i: if

$$F(x_i, d_j) = G_1(d_j) H_1(x_i) + G_2(d_j) H_2(x_i) + \cdots \qquad (9)$$

then, substituting into (7) and rearranging

$$\begin{aligned} G_1(d_j) \Big[\sum_i V_i H_1(x_i) &- kG_1(d_j) \sum_i H_1^2(x_i) \\ &- kG_2(d_j) \sum_i H_1(x_i) H_2(x_i) - \cdots \Big] \\ + G_2(d_j) \Big[\sum_i V_i H_2(x_i) &- kG_i(d_j) \sum_i H_1(x_i) H_2(x_i) \\ &- kG_2(d_j) \sum_i H_2^2(x_i) - \cdots \Big] \\ &+ \cdots = 0 \end{aligned} \qquad (10)$$

Substitution into (8) produces identical equations, hence (10) is a condition for best fit. From (10) we see that

$$\left. \begin{aligned} \sum_i V_i H_1(x_i) &= kG_1(d_j) \sum_i H_1^2(x_i) \\ &\quad + kG_2(d_j) \sum_i H_1(x_i) H_2(x_i) + \cdots \\ \sum_i V_i H_2(x_i) &= kG_1(d_j) \sum_i H_1(x_i) H_2(x_i) \\ &\quad + kG_2(d_j) \sum_i H_2^2(x_i) + \cdots \\ \text{etc.} & \end{aligned} \right\} \qquad (11)$$

These simultaneous equations give values of $G_1(d_j)$, $G_2(d_j)$, $\cdots G_n(d_j)$, from which n parameters can be obtained.

Solution by numerical methods—Assume that $F(x, d_j)$ contains only one parameter, say z.

By solving (7) and (8) simultaneously, we obtain a condition for best fit

$$\frac{\sum_i V_i F(x_i, z)}{\sum_i F^2(x_i, z_i)} = \frac{\sum_i V_i \dfrac{\partial F(x_i, z)}{\partial z}}{\sum_i F(x_i, z) \dfrac{\partial F(x_i, z)}{\partial z}} \qquad (12)$$

By substituting a sequence of trial values of z, its best-fit value Z can be obtained.

A solution can also be obtained by consideration of

$$\sum_i V_i F(x_i, z) \Big/ \sum_i F^2(x_i, z)$$

as a variable.

If Z in (7) is replaced by the variable z, and k by a variable y, then y can be considered a function of z, which approaches k as z approaches Z. Thus the behavior of y is an indicator of the nearness to Z, its best-fit value. Thus, if $F(x_i, z)$ be computed for a sequence of trial values of z, the nearness of this quantity to the observed V_i will be a measure of z's closeness to Z.

Or y can be substituted for k in other equations to give a solution. For example, for our case with only one unknown parameter Z substitute y for k and z for Z in (6), giving

$$\sum_i y[V_i - yF(x_i, z)] \frac{\partial F(x_i, z)}{\partial z} = 0 \qquad (13)$$

Since

$$y = \sum_i V_i F(x_i, z) \Big/ \sum F^2(x_i, z)$$

z can be determined by substituting a sequence of trial values of z into (13).

The method developed by *Legge* and *Rupnik* [1943] for solutions for parameters in relationships of seismic velocity to depth by the direct application of least squares is a special case of this.

Solution by comparison of $yF(x_i, z)$ *with observed values of* V—Let us consider a theoretical example to illustrate the method. Suppose that a profile across a thin, vertically polarized dike can be represented by the first-order approximation [*Nettleton*, 1941]

$$V_0 - V = 4Im(1/Z)x^2/(x^2 + Z^2) \qquad (14)$$

where m is the width of the dike, and V_0 is the value of V at $x = 0$, over the peak of the anomaly.

As the anomaly is symmetrical, we need to consider only values in the positive range of x. Suppose that $Z = 1.0$ miles, $4Im = 1.0$ emu miles, and x is taken at every 0.2 mile up to 1.6. Then from (14) we have the first two columns of Table 1.

Let us, from these data, attempt to arrive back at the values for Z and $4Im$.

For (14), $k = 4Im$, and

$$F(x, z) = (1/Z)x^2/(x^2 + Z^2)$$

Table 1 gives the quantities needed to calculate y over a range of trial values from $z = 0.6$ to 1.4 miles.

All that is now required is to tabulate values of $yF(x_i, z)$ and of Δ, their deviations from the observed values of V, and inspect them to determine Z. For convenience they are arranged in Table 2.

The value of z for which the observed values of $(V_0 - V_i)$ are most nearly reproduced is clearly 1.0 miles, giving $4Im$ a value of 1.0 emu miles, the values with which we started. Note that as the value of z passes through the best-fit value Z, Δ for each x_i passes through zero in a manner depending on the value of x_i, as shown in Figure 1. This criterion is particularly valuable in calculations, and using it, Z can generally be determined quite satisfactorily. The whole calculation can be easily programmed for the electronic computer, which can print out Table 2 over as wide a range of z as may be needed. Z can then be picked off by inspection.

Solution when $F(x, z)$ can be expanded in functions of x—The profile over a wide, vertically polarized vertical dike is given by [*Peters*, 1948]

$$(V_0 - V) = 2I[\tan^{-1}(\chi - \mu) - \tan^{-1}(\chi + \mu) + 2\tan^{-1}\mu] \quad (15)$$

where V_0, V, I are the same as in the first example, with

$$\chi = x/Z, \text{ and } \mu = m/Z$$

If we apply Taylor's expansion to (15) when $m > x$, we can write

$$(V_0 - V) \simeq 4I\left[\frac{\mu}{(1+\mu^2)^2 Z^2}x^2 + \frac{\mu(\mu^2 - 1)}{(1+\mu^2)^4 Z^4}x^4 + \frac{1}{3}\frac{\mu(3\mu^4 - 10\mu^2 + 3)}{(1+\mu^2)^6 Z^6}x^6\right] \quad (16)$$

Eq. (16) is a series of the type in (9), where $k = 4I$,

$$G_1 = \mu/(1+\mu^2)^2 Z^2, \qquad G_2 = \mu(\mu^2 - 1)/(1+\mu^2)^4 Z^4,$$
$$3G_3 = \mu(3\mu^4 - 10\mu^2 + 3)/(1+\mu^2)^6 Z^6,$$
$$H_1 = x^2, \qquad H_2 = x^4, \qquad \text{and } H_3 = x^6$$

Thus, substituting into (11), we have

$$\left.\begin{aligned}
&\sum_i V_i x_i^2 \\
&\qquad = kG_1 \sum_i x_i^4 + kG_2 \sum_i x_i^6 + kG_3 \sum_i x_i^8 \\
&\sum_i V_i x_i^4 \\
&\qquad = kG_1 \sum_i x_i^6 + kG_2 \sum_i x_i^8 + kG_3 \sum_i x_i^{10} \\
&\sum_i V_i x_i^6 \\
&\qquad = kG_1 \sum_i x_i^8 + kG_2 \sum_i x_i^{10} + kG_3 \sum_i x_i^{12}
\end{aligned}\right\} \quad (17)$$

TABLE 1 – *Values of* $\sum_i (V_0 - V_i) \cdot F(x_i, z)\gamma/\text{mi}$

x_i	$(V_0 - V)$	$z = 0.6$ mi	$z = 0.8$ mi	$z = 1.0$ mi	$z = 1.2$ mi	$z = 1.4$ mi
mile	gamma					
0.2	4	0.67	0.28	0.16	0.09	0.06
0.4	14	7.17	3.50	1.93	1.16	0.76
0.6	26	21.68	11.68	6.86	4.34	2.89
0.8	39	41.70	24.35	15.21	10.01	6.86
1.0	50	61.40	38.12	25.00	17.09	12.03
1.2	59	78.40	51.13	34.85	24.53	17.82
1.4	66	93.05	62.17	43.70	31.68	23.55
1.6	72	105.10	72.00	51.85	38.35	28.95
	$\sum_i$	409.17	263.23	179.59	127.23	92.92
$\sum_i F^2(x_i, z)\text{mi}^{-2}$		9.53	3.88	1.80	0.91	0.48
y emu mi		0.43	0.68	1.00	1.40	1.94

TABLE 2 – *Values of* $V = yF(x_i, z)$ *and* $\Delta = [(V_0 - V_i) - V]$

x_i	$z = 0.6$ mi		$z = 0.8$ mi		$z = 1.0$ mi		$z = 1.2$ mi		$z = 1.4$ mi	
	V	Δ	V	Δ	V	Δ	V	Δ	V	Δ
mile	γ	γ	γ	γ	γ	γ	γ	γ	γ	γ
0.2	7	−3	5	−1	4	0	3	1	2	2
0.4	22	−8	17	−3	14	0	11	3	10	4
0.6	36	−10	31	−5	26	0	24	2	21	5
0.8	46	−7	42	−3	39	0	36	3	35	4
1.0	53	−3	52	−2	50	0	48	2	47	3
1.2	57	2	59	0	59	0	59	0	58	1
1.4	61	5	64	2	66	0	67	−1	70	−4
1.6	63	11	68	4	72	0	74	−2	78	−6

Simultaneous solution will give values for kG_1, kG_2, and kG_3, from which m, Z, and k can be obtained.

Let us take a theoretical example, with $Z = 1.0$ miles, $m = 2.0$ miles, and $k = 2.0$ emu. As before, the anomaly being symmetrical, consider only the positive range of x. From (15) we have

x, mi	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
$(V_0 - V_i), \gamma$	2	4	7	11	17	28	40	54	71	90

Let us now, from these data, attempt to arrive back at the original values for Z, m, and k.

Using the above values for $(V_0 - V_i)$, simultaneous solution of (17) gives

$$kG_1 = 16.7\ \gamma/mi^2; \qquad kG_2 = 1.6\ \gamma/mi^4; \qquad kG_3 = 0$$

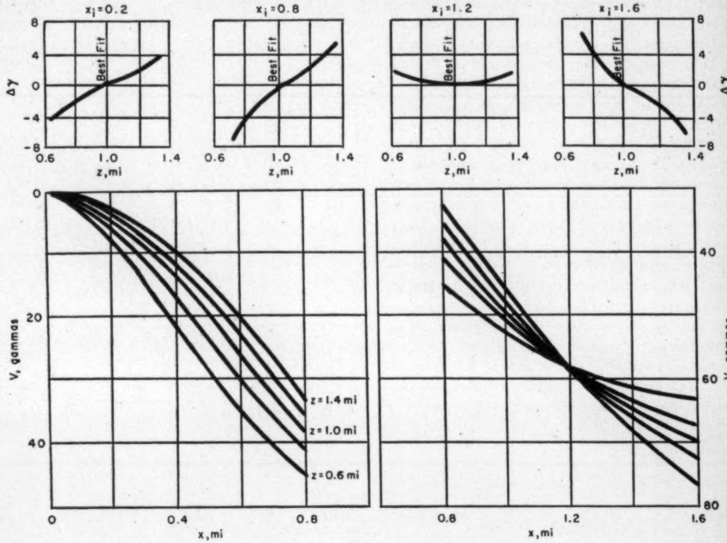

FIG. 1 – Variations of Δ with z; upper portion, manner of passage of Δ through zero as trial depth passes through best-fit value at various points on profile; lower portion, $(\sum V_iF_i/\sum F_i^2)F_i$, the second term of Δ for trial values of z; this equals V_i for best-fit z

Simultaneous solution of the three equations

$$\left.\begin{aligned} \frac{kG_1}{kG_2} &= \frac{(1+\mu^2)^2Z^2}{(\mu^2-1)} \\ \mu k &= kG_1(1+\mu^2)^2Z^2 \\ 3\mu^4 - 10\mu^2 + 3 &= 0 \end{aligned}\right\} \qquad (18)$$

gives

$$Z = 1.1 \text{ mi}, \qquad m = 2.2 \text{ mi}, \qquad k = 2.0 \text{ emu},$$

sufficiently close to the original values.

Application to gravity interpretation—The expression for the gravitational potential of a body is very similar to that for its magnetic potential. Its gravitational potential u_p at P is given by [*Heiland*, 1946, p. 144]

$$u_p = G\rho \iiint \frac{1}{r}\, dV \qquad (19)$$

where G = the gravitational constant, ρ = the density of the body, assumed to be uniform, and dV, r and limits of integration are the same as for (1). Comparing (1) and (19), we see that any least-squares methods developed for magnetic equations can also be applied directly to gravity equations.

Summary and conclusions—Least-squares methods have previously been applied in geophysics chiefly in the reduction of observations, and to such calculations as obtaining residuals and derivatives.

In the present paper it is shown that the equations of magnetic and gravity interpretation are such that for all bodies a solution for the parameters of the equation of the corresponding anomaly field is possible by least squares. In practice a certain amount of simplification is required unless the calculations can be programmed for the electronic computer, making it possible to treat quite complex solutions.

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Synoptic and Climatological Problems Associated with the General Circulation of the Arctic

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Abstract—Reasonably complete analyzed maps at sea-level, 700-mb, and 200-mb over the past decade have made possible a much improved picture of normal characteristics of the general circulation over polar regions including the interplay between synoptic and planetary scale patterns. Charts believed to represent fairly close approximations to long term normals are presented for January, April, July, and October, and an attempt is made to associate prevailing circulations with characteristics of the underlying surface, with season, and with type of synoptic development.

Large climatic fluctuations in circulation over periods of a month to a season are described and illustrated.

The short-period (day to day) variations over the Arctic and the associated prediction problems appear to be of the same nature as those of temperate latitudes and are thus amenable to present numerical methods. Longer-period fluctuations pose a much more difficult problem.

Introduction—During the past ten years the unprecedented accumulation of meteorological data at the surface and aloft over Arctic regions has led to a reasonably good picture of the synoptic meteorology and climatology of the Arctic atmosphere's general circulation. Earlier speculative interpretations of fragmentary information, involving frustrating efforts to interpolate in the horizontal and vertical, have now been replaced by a more solid framework provided by real data. These data, available for about a decade, cover much of the Arctic expanse and reach up into the substratosphere. While these newer data do not meet the requirements of many meteorologists, nevertheless, considering phenomena of ordinary synoptic scale and especially the scales of hemispherically interactive centers of action, the Arctic is relatively well represented by observations, certainly much more so than other areas of global meteorological importance like the Pacific.

From the new observations it turns out that many meteorologists of earlier generations might have made better inferences of the synoptic and climatological characteristics of the Arctic had they envisaged systems of greater similarity with those of the more familiar temperate latitudes, instead of seeking quite different models. It is now abundantly clear that cyclones and anticyclones traverse the Arctic in much the same fashion as in temperate latitudes, and upper level troughs, ridges, cyclones, and anticyclones, with dimensions and movements comparable to those of temperate latitudes, are synoptically common and transitory. As in temperate latitudes, pronounced autocorrelation exists from day to day; from week to week; and, to appreciable extent, from month to month. Indeed, the assemblage of several years of data suggests the existence of climatic fluctuations of the same order as those found elsewhere. In short, the atmosphere's general circulation over the Arctic appears to differ from temperate latitudes mainly in the statistics and not the kind of circulations. One may question, therefore, the degree of specialization indicated by the title, Arctic Meteorologist. On the other hand, the specialization leading to the title Tropical Meteorologist is more justifiable, for synoptic characteristics of the tropics are of another kind and scale from those of temperate latitudes.

The following remarks and illustrations are designed to highlight some of the circulation features of the Arctic gathered in the course of preparing hemispheric analyses and forecasts during the past decade. An attempt will be made to associate the most recent best estimates of the normal seasonal circulation patterns over Arctic regions with synoptic phenomena and thus assist in their explanation.

The normal circulation in the troposphere and lower stratosphere—In a recent paper [*Namias*, in press] the author displayed eight-year averages of sea-level pressure and 700-mb height over the Arctic for four months and compared these with earlier estimates of the 'normal,' particularly those made by the *U. S. Weather Bureau* [1952] and by *Baur* [1929]. The results of this study suggested that for most purposes the normal patterns of circulation of the lower troposphere over the

Arctic are reasonably well established, so much so that it is difficult to detect whether differences between the normal and averages of periods of five to ten years reflect transitory climatic fluctuations or erroneous earlier estimates of the normal. At any rate, while differences between such periods are undoubtedly statistically significant, they do not materially alter the large-scale aspects of the patterns. Thus, changes observed from one day, week, or month to the next are so overwhelmingly large that such 'errors' of the normals do not seriously interfere with current synoptic practices.

The eight-year averages to which reference is made are reproduced in figures 1 to 4, along with similar new charts for the 200-mb level. The sea-level and 700-mb charts were constructed from interpolations from twice-daily synoptic analyzed charts at closely spaced intersections of latitude and longitude. This method has the advantage of smoothing and detecting errors at the source of the daily map. The 200-mb charts for January and July, on the other hand, were computed as weighted means from the British Meteorological Office Average Charts [*Heastie*, 1955, 1956] for the years 1949–1953 and from U. S. Weather Bureau and Air Force daily 200-mb manuscript analyses during 1954–56. The only readily available data for the April and October 209-mb charts were extracted from U. S. Weather Bureau and Air Force daily analyses for 1951–56. The area 110°E to 20°E was not adequately covered during this period and is therefore left blank.

Figures 1 to 4 hardly require lengthy description for it is felt that meteorologists may easily draw from them whatever information is desired. However, there are certain primary features which call for explanations, and attempts in this direction stemming from years of synoptic practice shall be made with no illusions concerning their completeness. It is obvious that only when the observed circulations are exactly reproducible by quantitative methods or model experiment, a completely satisfying explanation is at hand. Perhaps the following remarks may suggest experiments or ideas for more quantitative assessment.

One prominent feature of the January upper-level charts which calls for explanation is the tri-cellular circulation in northern latitudes, which, to a considerable extent, is reflected as high up as 200-mb. While the presence of three waves in upper temperate latitudes has been known for many years, the existence of three closed cells in mid-troposphere at the tops of the

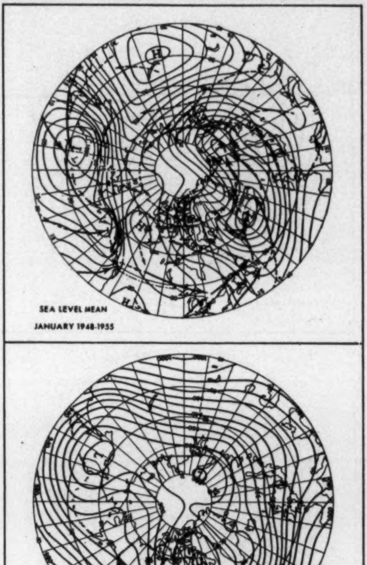

FIG. 1 – 'Normal' distribution of sea-level pressure, 700-mb height, and 200-mb height for January; arrows indicate principal (heavy) and secondary (broken) cyclone tracks [after *Klein*, 1957]; sea-level isobars labeled in mb (first two digits generally omitted, 700-mb contours in tens of feet, and 200-mb contours in hundreds of feet)

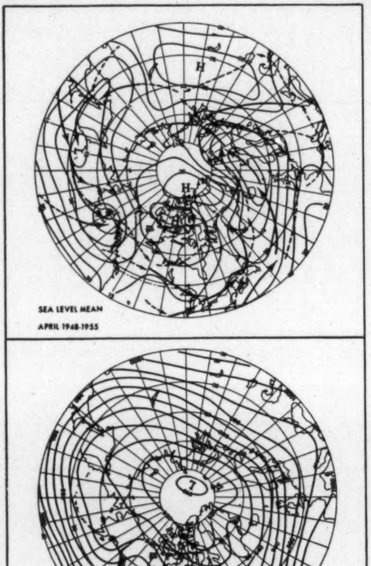
SEA LEVEL MEAN
APRIL 1948-1955
H
H
700 MB MEAN
APRIL 1948-1955
NORMAL 200 MB
APRIL

FIG. 2 – Same as Fig. 1, but for April

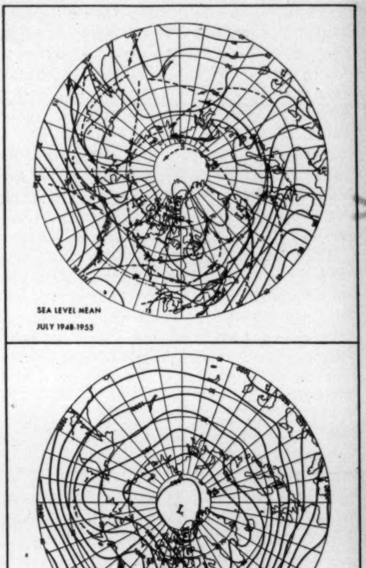
SEA LEVEL MEAN
JULY 1948-1955
700 MB MEAN
JULY 1948-1955
L
NORMAL 200 MB
JULY

FIG. 3 – Same as Fig. 1, but for July

planetary troughs emerges as a somewhat surprising feature. One might ask why such waves appear on the normal map, why they are where they are, and why the troughs are surmounted by closed cyclonic cells. Answers to the first and second questions must be sought partly in the geographical differences underlying the atmosphere's general west to east flow [*Rossby*, 1939; *Charney* and *Eliassen*, 1949; *Bolin*, 1950; *Smagorinsky*, 1953]. During winter the off-shore heating of cold air thrusts from the Asiatic monsoon anticyclone and the associated coastal cyclogenesis undoubtedly play a major role in creating a mid-tropospheric trough. To a lesser extent a similar trough tends to develop along the east coast of North America, but also an apparently strong forcing influence is the Rocky Mountain chain which, underlying the prevailing westerlies, creates a trough to the lee. These two 'forced' perturbations in the westerlies, the west Pacific and eastern North American troughs, are apparently sufficiently close so that the normally fast prevailing westerlies of January can frequently support both with little mutual interference. Eastward from eastern North America, however, the span between these two troughs is so great that the insertion of another perturbation, the European trough, becomes necessary to produce a dynamically stable system. In other words, as *Bolin* [1950] indicates, the European trough may be responsive to the flux of vorticity from the trough over eastern North America.

The closed cyclonic cells at the tops of these three troughs appear to be associated with the normal fields of baroclinicity of the atmosphere, perhaps in the following manner: It is now realized from the work of *Starr* [1954] and his colleagues that synoptic-scale phenomena of the weather map (the cyclones and anticylcones) must be introduced in order to explain the transfers of momentum, heat, and energy necessary to maintain the mean general circulation. The fundamental planetary trough systems of the general circulation more or less predispose the areas where these disturbances form and develop. Hence, off the east coasts of Asia and North America, the wave cyclones develop and move northeastward, feeding on the great baroclinicity established over the area between cold continent and warm ocean. These rapidly occluding disturbances eventually form the Aleutian and Icelandic lows, and appear in the mid-tropospheric wave patterns as strong maxima of cyclonic curvature (vorticity) in the Aleutians and east of Greenland. The sharp cyclonic bends in the 700-mb contours in these areas reflect vorticity sources generated by the intensifying cyclones. As a result, the upper level warm sector currents are frequently forced to curve from southeast toward northwest over the Bering Sea and eastern Siberia and also over Greenland and the Davis Strait. These currents, in turn, help to produce cut-off cold lows, whose statistical summations show up on the normal charts as the Kamchatka and Baffinland cyclones. Obviously, the cutting off of the tops of the two primary troughs automatically establishes the third cut-off low at the top of the Novaya Zemyla trough.

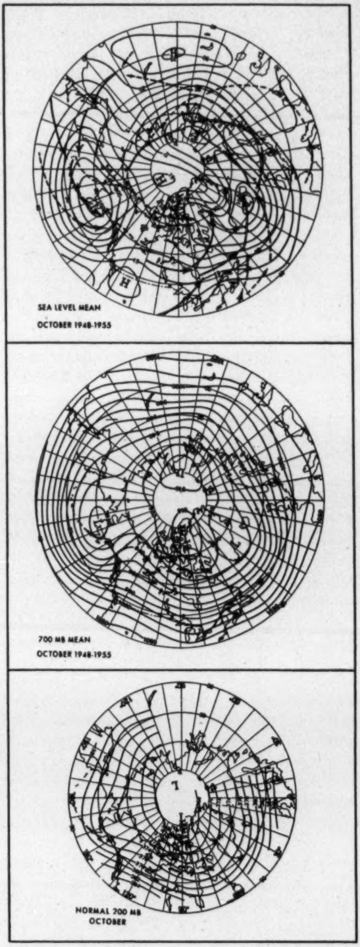

FIG. 4 – Same as Fig. 1, but for October

Synoptically, the process just described is a rather common wintertime phenomenon. Warm high-level ridges, and occasional anticyclones, frequently migrate westward and northwestward from the Aleutians and eventually make juncture with the Siberian anticyclone. Similarly, in the mid-troposphere warm pools cross westward and northwestward from Spitzbergen and Iceland, associated with depression of the Polar upper level vortex and not infrequently with a train of wave cyclones moving from southeast to northwest along a front with inverted air mass distribution.

The displacement with elevation of the primary sub-polar low systems in January indicates that in comparison to the Kamchatka low, the Icelandic low has a much greater portion of its westward displacement with height concentrated below 700 mb, a fact probably reflecting the greater asymmetry of geographical influences in eastern Asia than over northern Canada and Greenland. In other words, the stronger and deeper radiational cooling over northeast Siberia relative to the oceanic heating to the east effects a continued westward displacement with elevation of the low pressure center, while cooling by the Greenland Plateau (and frozen Davis Strait) results in a more or less thermal symmetry around the Baffinland low at the 700-mb level. Of course, normal isotherms at the 700-mb surface show this difference, a necessary condition from hydrostatic considerations.

The April charts (Fig. 2) show striking differences from January, perhaps the most noticeable of which is the marked relaxation in gradient at all three levels. This relaxation is due mainly to the weakening of both subpolar cyclones. At the same time the character of the Arctic Basin sea-level circulation becomes anticyclonic in character so that north of 70° a net rise of three to four millibars has occurred. Aloft, the three-celled structure is eliminated and replaced by a circumpolar vortex with southward trough extensions, two of which are in the primary subpolar cyclone areas. Probably in response to the slower zonal wind speeds at high latitudes, the number of waves around the hemisphere has increased from three to four, a new trough having emerged in the Gulf of Alaska. The filling of the mean Aleutian and Icelandic lows is associated with the reduced normal field of baroclinicity found in April along and off the east coasts of Asia and North America, so that northeastward moving disturbances, while still very frequent, do not have the supply of energy for development that they have in January. Besides, in April the frequency of blocking anticyclones at high latitudes is well near its May maximum as *Rex* [1950] indicated, so that the sub-polar lows are more often replaced by highs than in January. The increase in blocking activity is undoubtedly also associated with the increase in pressures over the entire Arctic Basin, although the physical reasons for this increase are not too clear. The author [*Namias*, 1950] prefers to ascribe the increased high latitude anticyclogenesis in spring to the relatively cold water and extensive ice areas found there, especially at this time of year. These cold areas are preferred regions for anticyclones and anticyclogenesis. Perhaps this tendency is due to the pronounced vertical stability observed over such areas. As *Wexler* [1943] pointed out, stability favors less leakage from the shallow friction layer at the bottoms of the anticyclones than instability over warm areas where the friction layer is deeper and the outflow greater. The extension of the Canadian-Arctic anticyclone to the relatively cold Hudson Bay in April seems to be a good example of this effect.

In July the normal upper air patterns are somewhat similar to April, at least as far as the central Arctic vortex and the troughs near Kamchatka, in the Gulf of Alaska and over eastern Canada are concerned. However, a tendency to a five-trough system now appears with the emergence of the Novaya Zemyla trough and suggested retrogression of the April European trough to the British Isles-Iceland area. The initiation of the new trough dominating eastern Russia and western Siberia appears to be a response to the marked decline in westerlies which sets in from spring to summer over the Eurasian area. The falling away of sea-level pressures from April, over the Arctic, is associated with the warming of the lower troposphere, since heights at the 700-mb level show an appreciable rise during this period. This rise is somewhat more pronounced over the peripheral land areas, as one would expect, so that a zone of thermal contrast becomes established near the rim of the Polar Basin which appears to give birth to frequent cyclones and peripheral cyclone movements (note cyclone paths in Fig. 3). Of course, frequent cyclones without strong anticyclonic counterparts result in the average low sea-level polar pressure observed in July.

Another interesting change in the July maps relative to April is the complete obliteration of the eastern (Gulf of Alaska) lobe of the Aleutian low. This appears to be due to the lack of a comparable baroclinic field between Alaska and the Gulf of Alaska in July compared to April. In other words, the heating in the interior of Alaska wipes out the strong thermal contrast southward

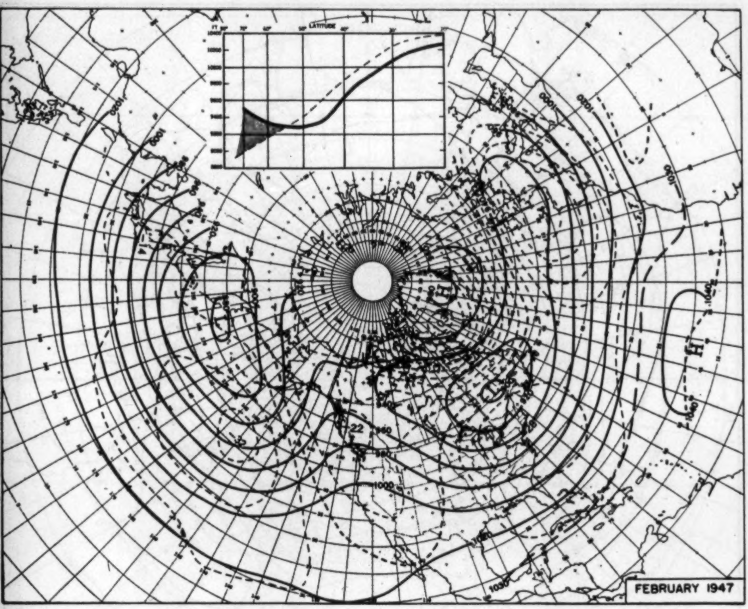

FIG. 5 – Mean 700-mb contours (solid) and departures from normal (broken) for February 1947

to the sea which is so effective in encouraging rejuvenation of old secondaries during winter and spring [*Winston*, 1955].

By October (Fig. 4) the wintertime type of pattern has already set in over the entire Arctic. The vigor of the circulation is indicated by the markedly strengthened gradients. The major characteristics of the three-wave and tricellular mid-tropospheric pattern show up clearly. However, the Aleutian low, both at the surface and aloft, is more in the nature of a single than a double center, so that the Kamchatka low, so predominant in January, is merely a cyclonic appendage to the center in the Aleutians. These differences between October and January show up strongly in the mid-troposphere (700-mb) and sub-stratospheric (200-mb) levels where there is almost an out-of-phase picture between these two seasons. This change, which in essence is a retrogression from October to January of the major trough-ridges system north of latitudes 55°N to 60°N in the Alaskan-Bering Sea and eastern Siberian area, is not readily explained. Perhaps it is associated with the stronger baroclinicity and cyclonic developments off Asia in January which permit cold occluded (and semi-stationary) lows to develop sooner and, hence, farther westward. This, in turn, is probably also associated with the stronger northeastward thrust of the Siberian high in January so that the strengthened easterlies north of Kamchatka retard the eastward motion of cyclones to the south. On the other hand, this difference may be induced by the different geographic influences on the higher latitude westerlies in October relative to January. At any rate, the strong asymmetry of the middle and upper tropospheric contour fields reflected in the great January displacements with elevation of the Aleutian Low seems to be absent in October when the 700-mb and 200-mb troughs are almost vertically posed over the surface cyclone.

At still higher levels than 200 mb, data should, in a few years, become sufficient to obtain a fair

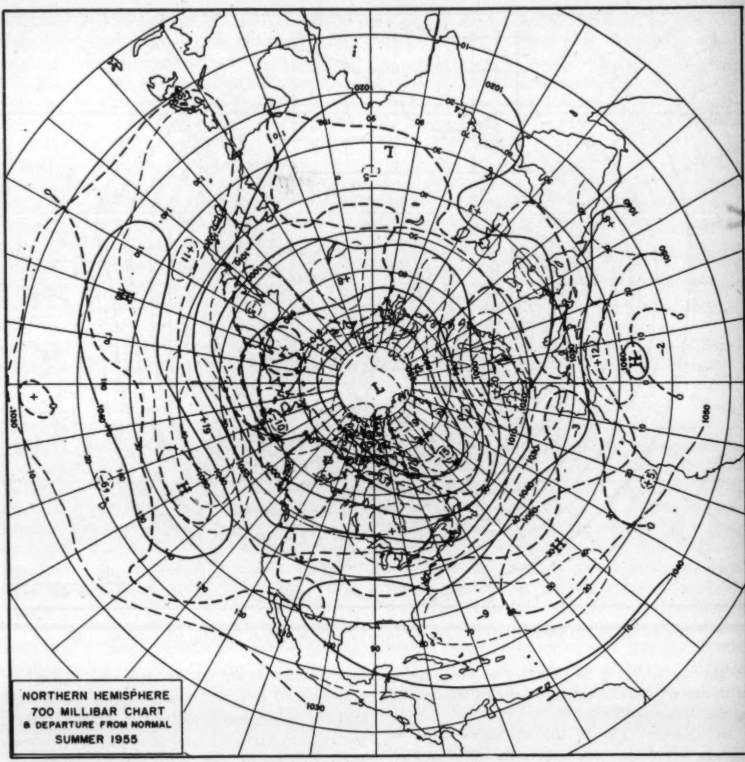

FIG. 6 – Same as Fig. 5, but for summer 1955

climatological picture of the polar night jet on a hemispheric scale. At present, it is possible to obtain only fragmentary information [*Lee* and *Godson*, 1957] of its seasonal variation, habitat, and strength. While it is tempting to draw climatological inferences from short periods of record, the great variability in meteorological elements between years must be borne in mind. Indeed, even for sea-level and 700-mb charts, for which a much more extensive source of data exists, there are suggestions that the eight-year period 1948–55 may have been abnormal in the sense that pressures were too high relative to a longer period average over the Baffinland-Davis Strait-Greenland area. (These persistent abnormalities, especially over periods of a year or two, form one of the central problems of long-range forecasting and should be kept continually in mind by students who plan to interpret the new IGY Antarctic data.)

Shorter-period climatic fluctuations—While data are inadequate to detail climatic fluctuations in the Arctic circulation of the order of years or decades, they are adequate to afford some insight into seasonal, monthly, and shorter period fluctuations. Perhaps one of the most striking aspects of Arctic circulation patterns is the tendency of a particular type to persist in broad-scale from day to day, and to persistently recur in the same season after only brief interruptions. There are, of course,

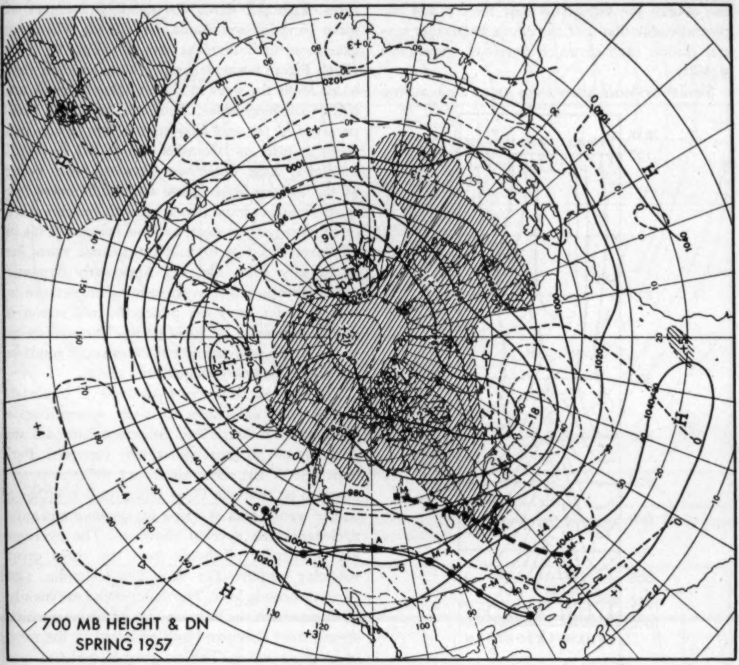

FIG. 7 – Same as Fig. 5, but for spring 1957; heavy arrow-pointed lines running through United States denote monthly course of negative (open) and positive (solid) anomalies appearing on maps for individual months, denoted by letters

synoptic scale variations associated with the transit of cyclones and anticyclones, but these appear to be governed by a larger scale and quasi-persistent circulation pattern, which may differ considerably from one season to the same season of another year. As a result of the serial correlation in daily, weekly, and monthly circulations, the magnitude of departures from normal (or from a long-period average) over the Arctic are surprisingly large. Examples of such anomalies at the 700-mb level for three periods, February 1947, the summer of 1955, and the spring of 1957, are shown in Figures 5, 6 and 7. Figure 5 illustrates a case where the cyclonic activity normally present over the polar cap was replaced by a great anticyclone, so that the sea-level prevailing westerlies of temperate latitudes were displaced about 20° southward of their normal latitude [*Namias*, 1947]. Figure 6 shows an unusually strong upper-level cyclone over the Polar Basin girdled by several strong positive anomalies associated with a northward displacement of the sub-tropical highs. The resultant strong westerlies along the rim of the Polar Basin were associated with an unusually high frequency and intensity of cyclones. Figure 7 illustrates an extensive excess mass over polar regions and apparently compensating deficits in the subpolar cyclones. On this chart are also indicated the paths of certain anomaly centers extracted from overlapping 30-day mean charts. The parallelism of these paths with the isopleths enveloping the polar anomaly suggests that the latter may have exerted a steering influence [*Clapp*, 1952], and such Arctic influences might be highly important for 30-day prediction.

From such routine happenings over the Arctic one obtains the impression that there is not one general circulation over the Arctic but rather several modes, each of which possesses remarkable stability.

Similar evidence arises from upper air temperatures. Figure 8 shows the monthly averages of some 10 years over Thule, Greenland. When one examines the individual months (Fig. 9) from which Figure 8 was derived, it becomes clear that at all levels the same month of different years are highly inhomogeneous. Thus, the minimum temperature in the mid-troposphere over Thule can occur as early as December and as late as April. Similarly, large differences between years occur at the 200-mb level. These latter differences frequently appear to be associated with the curvature of the flow pattern aloft, cyclonic being cold (as in January 1956, Fig. 10) and anticyclonic warm (as in January 1953, Fig. 11). Apparently dynamic considerations are of overwhelming importance in high latitudes, especially during the cold season, a point emphasized by *Riehl* [1950]. The sensitivity of the Arctic to dynamic influences could result in rewarding studies of singularities there.

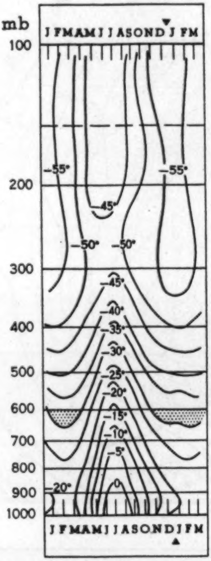

FIG. 8 – Average monthly temperatures over Thule, Greenland, for the ten-year period 1947–1956

The synoptic short-period problem—As indicated earlier, the differences between synoptic-scale phenomena of Arctic and temperate latitudes are probably not as great as formerly supposed. Perhaps one of the more significant differences appears to be that the Polar Basin itself is either a sort of transit area or a sink for cyclones and anticyclones which develop elsewhere. The cyclones are principally off-shoots from the three great subpolar centers: The Aleutian, Icelandic, and Novaya Zemyla lows. The anticyclones are mainly off-shoots from the Siberian high or systems which spread from Greenland and eastward in the form of blocking waves. The entrance of cyclones into the Polar Basin is especially favored when blocking or high latitude anticyclogenesis is pronounced,

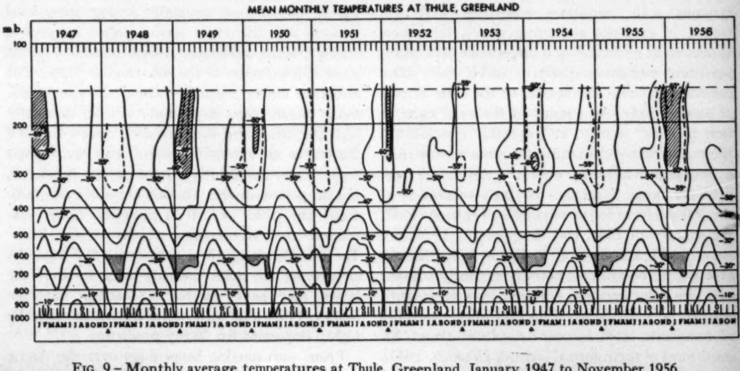

FIG. 9 – Monthly average temperatures at Thule, Greenland, January 1947 to November 1956

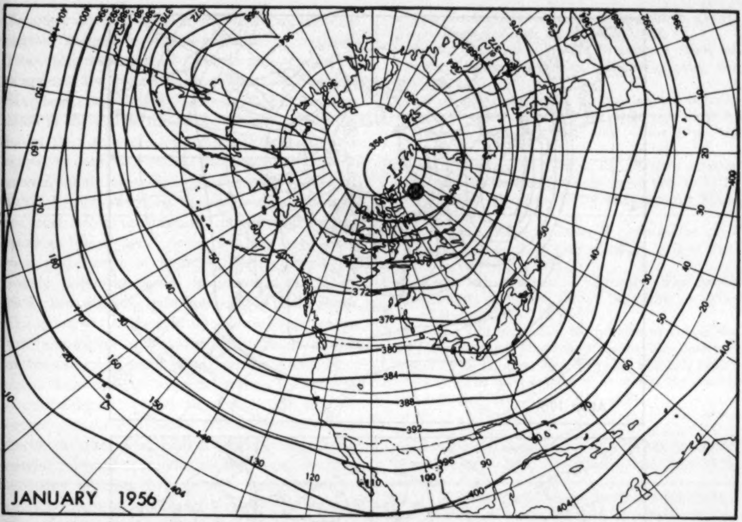
JANUARY 1956
356
360
364
368
372
376
380
384
388
392
396
400
404

FIG. 10 – Monthly mean 200-mb contours for January 1956 when temperatures at this level over Thule were much colder than normal

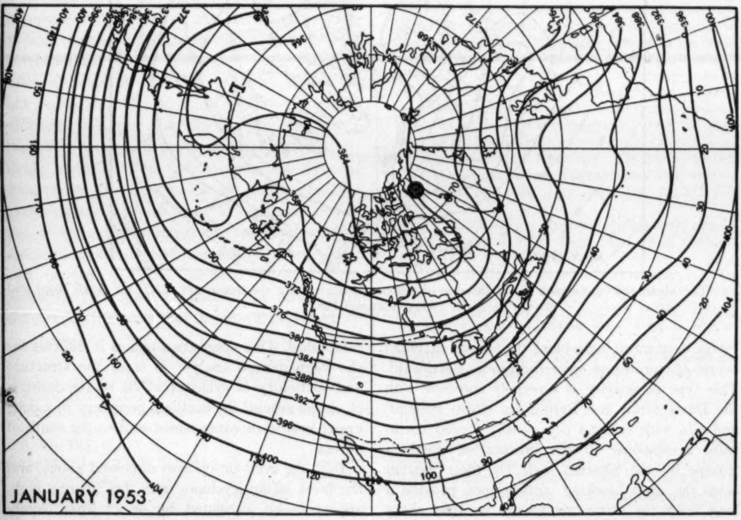
JANUARY 1953
364
368
372
376
380
384
388
392
396
400
404

FIG. 11 – Monthly mean 200-mb contours for January 1953 when temperatures at this level over Thule were warmer than normal; note difference in curvature over Thule (heavy circle) compared to Fig. 10

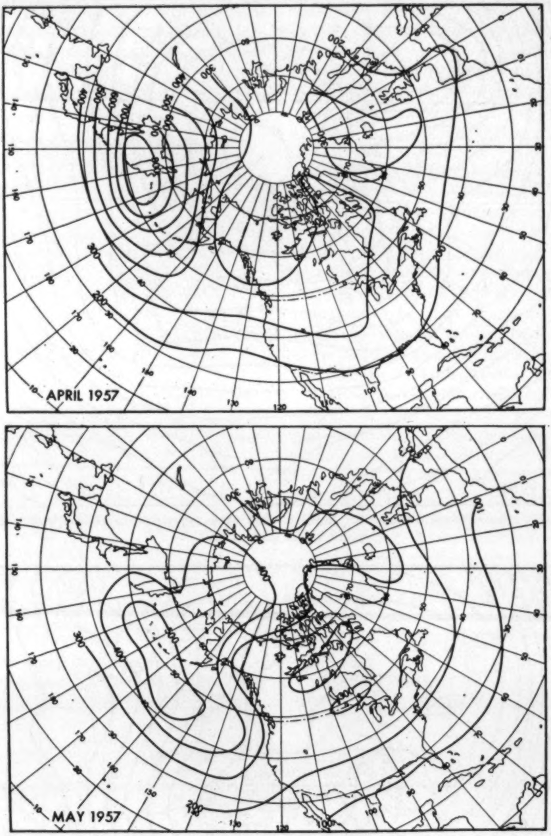

FIG. 12 – Mean absolute errors (ft) in 48-hour barotropic prognoses (by electronic computer) for April (top) and May (bottom) 1957

for the deep warm highs block the normal eastward course of storms and steer them more northward. This type of activity is especially common with the Davis Strait and Bering Sea storm systems, and also with systems occasionally forced northward in response to the invasion of northern Europe by the Siberian high. On their western sides the deep blocking anticyclones provide a long fetch for warm air masses so that sharp meridional or even NW-SE oriented fronts are established. This orientation makes it difficult for the inexperienced analyst to trace the structure and continuity of cyclones which rotate counterclockwise around the northern periphery of a deep upper level vortex suppressed well to the south of normal.

Both the cyclonic systems discussed above, and the break-off anticyclones from the Siberian high, appear to be instigated by or at least closely associated with imbalances of the high latitude planetary wave systems which often respond in a manner suggestive of redistribution of vorticity. Thus, the results of 24- and 48-hour barotropic prognoses by electronic computer at Suitland, Maryland, the United States show that for large areas of the Arctic the errors are not greatly different than they are for temperate latitudes and, moreover achieve a skill at least equal to those of conventional forecasters [*Staff members, JNWP*, 1957]. Figure 12 shows the mean absolute errors for such 48-hour forecasts made daily during April and May 1957. Aside from the large errors over and north of eastern Siberia, which are largely boundary errors [*Cressman* and *Hubert*, 1957], the success is quite comparable to elsewhere. The extension of the grid to cover a larger area of the hemisphere will undoubtedly result in still better numerical predictions over the Arctic. Here again there appears to be no reason to treat the Arctic separately from temperate latitudes. Of course, this does not imply that special features of Arctic weather and climate should not receive careful study. But it indicates that more complete solutions relating to temperate latitude circulations, perhaps obtainable with the help of machine prognosis, may also be solutions for the Arctic atmosphere.

In summary, the principal synoptic and climatological problems of the Arctic atmosphere as seen today appear to be not so much with determination of the average or normal circulations, although further data are always welcome, but rather with the explanation of the seasonally different patterns and particularly the stable though anomalous patterns that arise during particular months. This is in essence the dynamic climatology of the circulation. Of course, the gathering and summarization of statistical properties of the Arctic atmosphere, together with descriptive studies will be helpful, both practically and toward a better physical understanding. Similarly, case studies detailing the structure of the Arctic air masses and fronts will be helpful.

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The Accuracy of Wind-Speed Estimates at Sea

CHARLES F. BROOKS AND ELEANOR S. BROOKS

Abstract—Most wind reports at sea come from merchant ships without anemometers. The Beaufort scale is used, the units of which are now defined principally in terms of sea disturbance. A study of 1315 pairs of measured and estimated winds made on U. S. weather ships shows that the estimated speeds corresponded to the measured within 1–3 knots (same Beaufort number) in 60 pct of the cases; 28 pct were underestimated and 12 pct overestimated. The greater frequency of underestimates than of overestimates is apparently owing mainly to the fact that the anemometers (at 20–30 m) on the weather ships are higher than the (10 m) elevation for which the speed equivalents of the Beaufort scale were established, but partly also to the extra mileage of the anemometer owing to the rolling and pitching of the ship.

Changes in wind speed occur so often that lag in the reaction of the sea is the most common cause of error in estimates. Another source of trouble is the sea—air temperature difference, a cold wind relative to the sea producing larger waves than a warm wind. Decreasing winds that are also cold are especially likely to be overestimated, and increasing ones that are warm, underestimated.

On weather ships and some merchant vessels, wind speed at sea is determined by anemometer. Merchant ships without anemometers now report winds in knots converted from Beaufort. How do measured and estimated speeds compare? The comparison is somewhat troublesome. We have no standard true wind speed, such as might be obtained from a fixed anemometer. We are comparing winds at different levels, using two methods subject to different types of errors. Discussions of the problem by meteorologists of eight countries were recently published by the *World Meteorological Organization* (*WMO*) [1955, pp. 19–27].

Anemometers at sea—Anemometers on U. S. weather ships are placed at an elevation of 20–30 m on the mast or yard-arm, to minimize the influence of the obstructing bulk of the ship. Since the Beaufort estimates are officially matched against winds measured at 10–15 m, the measured winds at 20–30 m should exceed the official equivalents on the average by about three to five per cent, according to *Roll* [1951].

Over-registration by cup anemometers is caused by gustiness; it is also favored by the extra miles of air the anemometer travels owing to the rolling and pitching of the ship, which is magnified high on the mast [*WMO*, 1955, pp. 20–22]. On the other hand, in very light winds the anemometer may fail to start or keep going. Nevertheless, anemometer speeds are obviously more accurate than estimates from sea disturbance, and may be used with some assurance for determining the errors of the latter.

Estimates of wind speed—The Beaufort scale was based originally on the speed of an ideal sailing frigate with all sail set (force 0–4), or on the amount of sail it could carry (force 5–12). When sailing ships were no longer in common use, sea disturbance was correlated with the Beaufort rating of the wind; also Beaufort force B equivalents in knots have been standardized from readings of anemometers at an effective height of 10–15 m above sea level [*WMO*, 1950–56]. For a detailed historical account and critique, see *Verploegh* [1956]. A revised standard proposed by *Verploegh* [1956], based on two sets of new data coordinated with seven older sets, has recently been recommended by the Commission for Maritime Meteorology for adoption by the *WMO* [1957, pp. 29–30].

Wind estimates may vary considerably among observers. On two trans-Atlantic voyages author C. F. B. made 57 careful estimates at regular ship observation times. The ships' observers estimated the same force as C. F. B. 36 times, one Beaufort different, 16 times, and two different, five times. *Lisitzin* [1948] checked Finnish light ships. One had five observers from 1921–1940, and their average reports ranged from 2.4 B to 3.7 B, while other light ships showed no comparable changes.

Wind speed at sea, when not changing rapidly, can be estimated by the amount of sea disturbance [*WMO*, 1950–56; *Burgess*, 1950; *U. S. Weather Bureau*, 1954], if due account is taken of several modifying factors [*Kirk*, 1948; *Roll*, 1950], including whether the wind is warmer or cooler than the water.

The temperature factor in estimates—It has long been known that winds colder than the sea raise bigger waves than those warmer and of the same speed [*Humphreys* and *Brooks*, 1920]. C. F. B. [*WMO*, 1955, p. 20] has cited cases of a wind of 3 *B* over a glassy sea of cold water and of another of 5 *B* making large waves with many white caps on stretches of warm water, but only medium waves and few white caps, of normal 3–4 *B* size on an intervening zone of cold water.

Roll [1951] found that when the air was 1 C deg warmer than the sea, the wind at 20 m height had to be 7.5 m/s to provide the actual surface wind of 3 m/s required to raise waves of 3 *B* grade; with no temperature difference, a wind of 5.8 m/s was sufficient; but when the air was 1 C deg colder there was enough vertical mixing to raise a 3 *B* sea with a wind at 20 m of only 4 m/s. *Roll* [1951] has now presented data from North Atlantic weather ships demonstrating numerically that "with wind of equal force waves will become higher and steeper in case of cold air than they will become in warm air." With winds of 13–37 k (4–8 *B*) waves averaged 23 pct higher and 14 pct steeper when the air was 6.7 C deg (12 F deg) colder than when 2 C deg (3.6 F deg) warmer than the sea.

Fleagle [1956] confirmed Roll's findings, from a study of 150 cases observed at Station Hotel, 36°N, 70°W. He took care to eliminate the factor of varying fetch.

Colder water produces a more or less stable layer of chilled air which inhibits wind thrusts to the surface, especially in winds not exceeding 4 *B*; it cools the entire turbulent layer of air and thereby reduces the general turbulence and therefore the strength of the thrusts reaching the cool protecting layer of air [*Humphreys* and *Brooks*, 1920; *Båth*, 1949; 1951, pp. 295–304; *Bernasconi*, *Bossolasco*, and *Dagnino*, 1952]; and, lastly, it increases the vertical gradient of wind speed, so that the wind at the surface will actually be considerably less than that on the mast [*Roll*, 1952]. There is an additional factor, though usually a small one, namely, the density of the air: thrusts of warm, humid air under low atmospheric pressure are less powerful at the same speed than those of cold, dry air under high pressure. The viscosity of sea water, which varies with its density, is also a minor factor. Warm winds over a colder sea, therefore, tend to be underestimated and vice versa.

A NEW STATISTICAL STUDY

The relationship between wind estimates and measurements was investigated by us in a series of 1315 observations of wind speed made for the purpose from Feb.–Aug. 1951 on eight different U. S. weather ships at and near Station Dog in the North Atlantic (lat 44°N, long 41°W). Conical cup anemometers were employed, mounted on masts 70–100 ft (20–30 m) above the sea. Conical cups over-register less than hemispherical ones in a gusty wind [*Scrase and Sheppard*, 1944].

GENERAL RELATIONSHIP

Estimated versus measured speeds for each force Beaufort—Table 1 shows wind measurements by knots for each estimated force Beaufort. Column 2 shows wide scattering. Indeed, winds of 25 knots were estimated all the way from 3 *B* to 8 *B* but were most frequently called 6 *B*. Thus, 25 knots was classified as 6 *B*. Similarly, 10 knots, which ranges from 2 *B* to 6 *B*, was assigned to 3 *B*. Column 3 divides the measured speeds among the several Beaufort numbers at which they were most frequently estimated, as just described. Our data conform more closely to the previous official Beaufort scale in general than to the proposed new

TABLE 1 – *Measured (knots) for each estimated force (Beaufort), 1315 cases (see Fig. 1)*

Estimated force *B* 1	Extreme range 2	Limited range 3	1947 official Beaufort scale 4	Proposed official Beaufort scale 5
1	0–7	0–3	1–3	1–4
2	0–15	4–6	4–6	5–8
3	3–25	7–10	7–10	9–12
4	7–26	11–18	11–16	13–16
5	9–30	19–22	17–21	17–21
6	10–34	23–27	22–27	22–26
7	20–39	28–34	28–33	27–31
8	24–40	35–40	34–40	32–36
9	32–47	41–47	41–47	37–42

TABLE 2 – *Beaufort force as estimated from the state of the sea surface E versus Beaufort force as measured by anemometer M; all observations (1315)*

Set	No. of cases	E < M pct	E = M pct	E > M pct
1	101	25	60	15
2	179	24	58	18
3	192	46	47	7
4	133	27	53	20
5	182	22	61	17
6	119	23	69	8
7	190	38	53	9
8	219	15	81	4
1–8	1315	28	60	12

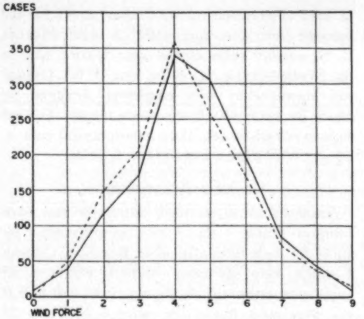

FIG. 1 – Numbers of cases of wind speed by Beaufort number out of a total of 1315; solid line, converted to *B* from anemometer readings; dashed line, estimated from sea disturbance

standard, but show measured values a little high for the force at which they were estimated, especially in the middle of the scale.

Verploegh [1956], on the contrary, found measured values too high for light winds and too low for heavy winds, the middle of the scale showing the best agreement. His scale is adjusted for anemometers at a height of 10–15 m; ours were at 20–30 m.

It was hardly practicable to assign a definite average value in knots to each force *B* in our series because the anemometer data were not recorded too closely. Observers appeared to favor multiples of 5, and, to a lesser extent, even over odd values. For example, a tabulation of four sets of data from four different ships showed the following distribution: 18 knots, 31 cases; 19 knots, 18 cases; 20 knots, 53 cases; and 21 knots, 15 cases.

Estimated versus measured speeds for each set of observations.—Table 2 and Figure 1 show clearly that estimated wind speeds E were more frequently below, than above, the measured M. Measured and estimated force agree in 60 pct of the cases, however, and the difference exceeded one force Beaufort in less than five per cent of the cases. *Verploegh* [1956, p. 14] found that if measured velocities are considered fixed, the error in estimates may amount to 0.4 *B* in ⅔ of the cases. Night observations showed about the same degree of accuracy as those made by day.

SOURCES OF ERRORS IN ESTIMATES

Errors of estimation when wind speed is changing—To analyze further the causes of disagreement, we compared estimation of changing winds with estimation of well-established winds for measured 4 *B*, the most frequent force. A case was counted as changing if 4 *B* had not been recorded at either of the two previous observations. Observations were taken at three-hour intervals. By contrast 4 *B* was counted as well established if that force had been recorded at both previous observations. The results are shown in Table 3. Naturally, established winds are most likely to be correctly estimated.

TABLE 3 – *Effect of changing, measured wind speed on estimated speed*

Wind character	No. of cases	E < M	E = M	E > M
		pct	pct	pct
4 *B*, changing winds	137	28	49	23
4 *B*, established winds	70	13	87	0
All winds (from Table 2)	1315	28	60	12

Because of the overall tendency for estimates to be lower than measured values, most profiles in these figures are unsymmetrical; that is, the underestimates exceed the overestimates. The profile for all winds is intermediate between those for 4 *B* changing and 4 *B* well-established.

This sampling encouraged a more extended test of changing winds, with less narrow limits. Every wind was classified as 'decreasing,' 'no change,' or 'increasing,' according to whether the measured force Beaufort at the preceding observation was less, the same, or more. Wind speed only was considered. There were 373 cases of 'decreasing,' 550 of 'no change,' and 384 of 'increasing'; 8 were indeterminate, being the first ones in each of the eight series. The estimated values clearly show a lag effect (Fig. 2).

When judging from sea disturbance, there is a tendency to underestimate rising winds and to overestimate decreasing winds. *Verploegh* [1956] writes of the retardation with which the sea follows changes in the wind field: "After a stormy period normal wind velocities which are usually estimated 0.5 to 2 knots too low are now estimated too high."

Errors of estimates when sea and air temperatures differ markedly—Sea–air temperature differences also affect wind-speed estimates. It is generally recognized that a wind warmer than the sea tends to produce smaller waves than a wind of equal speed which is colder than the sea. Since wind speed is estimated from sea disturbance, this favors underestimates of warm winds and vice-versa. In 82 out of 1315 cases (six per cent) the air was at least 3.6 F deg. (2 C deg) warmer than the sea. Of these 82 cases, 30 were concentrated in one week (July 31–Aug. 6). In other locations, for example, over the Labrador current, greater contrasts might occur. More often the air is colder than the sea, and by a larger amount; for example there were 196 cases (11 pct) of air at least 9.0 F deg (5 C deg) colder than the sea.

Figure 3 shows the effect of sea–air temperature differences on Beaufort estimates. The record for warm winds (Fig. 3) very closely resembles that for all winds (Table 2). The number of cases (82) is somewhat small, however, especially since 36 came from one ship and 31 (86 pct) of these are correct estimates. The other seven sets show 43 pct underestimates, 48 pct correct, and 8 pct overestimates. The cold winds show a slight excess of overestimates.

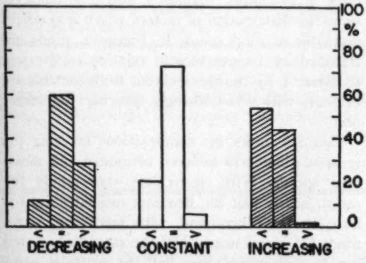

FIG. 2 – Effect of decreasing or increasing wind (all speeds) on estimated force derived from the disturbance of the sea surface

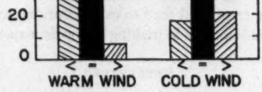

FIG. 3 – Effect of relative temperatures of sea and air on estimates of wind speed from the disturbance of the sea surface

TABLE 4 – *Temperature of water (°F), and winds of 4 B*

E < M				E = M				E > M			
Cases	Temp.		Diff.	Cases	Temp.°		Diff.	Cases	Temp.		Diff.
	Sea	Air			Sea	Air			Sea	Air	
•	•	•	•	•	•	•	•	•	•	•	•
108	62.6	61.6	1.0	230	64.4	63.0	1.4	25	63.6	59.1	4.5

TABLE 5 – *Average sea-air temperature differences when wind has been measured 5 B during at least the last six hours, subdivided according to wind estimates*

With continuing wind at 5 Beaufort	E < M	E = M	E > M
Av. sea–air temp. diff., F deg	0.7	5.0	(10.7)
Cases	13	47	2
Per cent of 62 cases	21	76	3

TABLE 6 – *Average wind speed as measured for cases when estimated wind was 5 B*

Category of air-sea temperature contrast at 5B	Cases	Wind speed measured
		knot
General average	250	20.5
Air 3.6 F deg or more warmer than sea	13	20.6
Air 9.0 F deg or more colder than sea	43	19.7

More cases can be obtained by averaging all sea–air temperature differences, as in the sample in Table 4 which is restricted to winds estimated at 4 *B*, the most frequent force. In this group of cases, when estimates exceed the measured wind the winds average definitely colder than the sea. Air temperatures are taken at a height of about 20 ft above the water.

To bring out temperature control more clearly, we tabulated 62 cases of established winds measured 5 *B*. These are summarized in Table 5.

Classification by temperature difference gave consistent but not definitive results (Table 6), as the opposite extremes of sea–air difference showed an average difference of only about one measured knot in the winds involved (20.6 and 19.7 knots, respectively). *Verploegh* [1956, p. 15] did not find any systematic differences in equivalent velocities at 7 m for unstable and stable conditions. Apparently, 7 m is so near the surface that the effect of a cold sea in damping wind speed is already strongly felt.

Joint effect of changes in wind speed and sea–air differences in temperature—Now let us look again

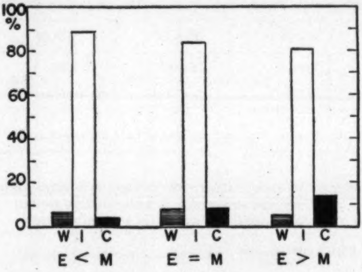

FIG. 4 – Relation of estimated to measured wind subdivided according to the temperature of the wind relative to that of the sea surface; the limits of the temperature classes are: warmer (W), at least 3.6 F deg (2 C deg) warmer; intermediate (I), between less than 3.6 F deg warmer and 9.0 F deg colder; and colder (C), at least 9.0 F deg (5 C deg) colder

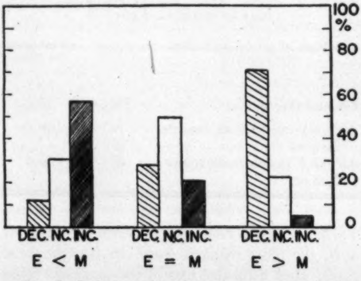

FIG. 5 – Relation of estimated to measured wind subdivided according to the trend in wind speed since six hours earlier; the wind-speed classes are: decreasing (DEC), a decrease of at least one Beaufort number; no change (NC), no change in Beaufort number; and increasing (INC), an increase of at least one Beaufort number

at the combined effect of changing wind speed and contrasts in air and sea temperature. In Table 2 and Figure 1 a general tendency for measured values to exceed estimated was shown, and we indicated that this was probably caused by the height of the anemometer being greater than that for which Beaufort numbers were standardized and to the extra mileage of the anemometer owing to the rolling and pitching of the ship. After our analysis of the sea versus air temperature factor it is now clear that the tendency for measured to exceed estimated winds cannot be ascribed to

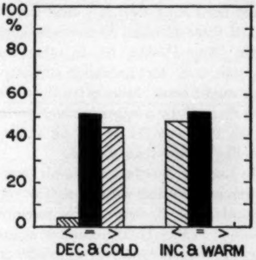

FIG. 6 – Combinations showing the greatest differences between estimated and measured wind speed

winds being warmer than the sea, because relatively cold winds are more frequent in this group.

Changes in wind speed occur so often that lag in the reaction of the sea is a common source of error in estimates. Figures 4 and 5 attempt to show the distribution of factors which may affect estimates of wind speed. In Figure 4, winds are classified by temperature in relation to the sea, in Figure 5, by change of speed. Both controls are evident, with wind changes playing the larger part.

Figure 6 shows the combinations favoring the greatest differences between estimated and measured speeds. With decreasing, cold winds (67 cases), nearly half the Beaufort estimates are too high; on the other hand, with increasing, warm winds (21 cases) nearly half the estimates are too low. In each group about half the estimates agree with the measured Beaufort. The number of cases is hardly adequate.

The best agreement (87 pct) between estimates and measurements appears in Table 3, based on 70 cases of well-established winds, force 4 *B*. It so happens that this group contained four winds 3.6 F deg warmer than the sea, and only two winds 9.0 F deg colder, all listed among the correct estimates.

It would appear that lag in sea response to changing winds is a larger source of error than sea–air temperature differences. For climatic averages lag errors will tend to cancel out, but are more of a disadvantage in making synoptic maps.

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Effective Coefficients of Diffusivity for Atomic Bomb Clouds at One Thousand to Two Thousand Miles

EUGENE M. WILKINS

Abstract—Twelve selected radioactivity profiles through atomic bomb clouds, made one to two days after detonation, yield an average 'effective' coefficient of diffusivity, $K = 2.7 \times 10^8$ cm² sec⁻¹.

During the Nevada weapons tests carried out by the Atomic Energy Commission in January-February and October-November, 1951, aircraft flights were made through the nuclear clouds at various distances from the burst point to obtain radioactivity profiles. These measurements provide useful estimates of large-scale diffusion.

Machta and others [1957] have given the profiles for tests in January and February, together with explanations of sampling techniques and data limitations. The additional profiles used in this analysis are for clouds formed in the October-November tests, and these are sufficiently reproducible from the peak activities and σ values (standard deviations of radioactivity distribution) listed in Table 1.

The coefficients of lateral eddy diffusivity K in Table 1 were calculated for the radioactivity profiles that made a reasonable fit to a Gaussian curve, assuming that the classical Fickian law of diffusion is applicable. These are 'effective' coefficients, containing as they do the effects of wind shear and settling of particles. There was not a sufficient range of times and distances in the data to seek a trend of variation of K on these parameters. The average K for all 12 profiles may be adequate for estimate purposes within the range of circumstances in which they were determined, since the extremes differ from each other by less than a factor of six.

Richardson [1926] calculated $K = 5 \times 10^8$ cm² sec⁻¹ for the spreading of volcanic ash—an example of diffusion on a somewhat larger scale than the bomb clouds, but one in which K was comparable with the largest values listed in Table 1.

Two authors have computed K for this scale of diffusion using moisture variations along isentropic surfaces. *Grimminger* [1941] quotes a range of 3 to 87×10^8 cm² sec⁻¹ for mean monthly isentropic charts, and 6 to 390×10^8 cm² sec⁻¹ for daily charts. *Miller* [1948] quotes a range of 40 to 1000×10^8 cm² sec⁻¹ for daily charts. Possibly, the greater K values result from the use of profiles that were not good approximations to Gaussian curves (such profiles were rejected in the present analysis), but limitations in their data must also result from the inaccuracies of mixing ratio measurements.

Moore and others [1954] obtained $K = 4 \times 10^7$ cm² sec⁻¹ from the spread of constant-level balloons traveling about the same distances as did the bomb clouds. This is an order of magnitude less than the mean for the bomb clouds. Presumably, the three-dimensional nature of the debris, permitting vertical wind shears to act, contributes to this difference. Also, the initial separation of the balloons was quite small (of the order of yards) compared with the initial diameter of the bomb cloud (of the order of miles), and thus the eddies effecting balloon separation were restricted to the smaller sizes.

The distances given in the table are taken along the cloud path, determined from the meteorological trajectory nearest the sampling altitude. Trajectory and sampling altitudes were the same for all but five of the profiles, and for these the difference was only 1000 to 2000 ft.

In some cases, the straight line distance from the burst point was less than half of the path length, and one cloud made almost a complete circle around a stationary cyclone, not being intercepted by the sampling aircraft until the cloud had returned almost to the point of origin.

The clouds represented in the table cover a wide range of situations with regard to wind shear. Also, the surface burst was very much different from the others in that the inclusion of soil in the original fireball resulted in much larger and hence faster-settling radioactive particles. Nevertheless, the K values as computed for this cloud were very near the mean for the group.

It is interesting that one-third of all of the profiles taken in a complete traverse of the cloud gave a good fit to a Gaussian curve. An additional one-third could have been fitted crudely out to about 2σ. It was noted also that in several cases where the cloud became divided into two segments, giving two maxima in the radioactivity profile,

TABLE 1 – *Eddy diffusivity coefficients for atomic bomb clouds*

Date	Time GCT		Burst height above ground	Maximum rise	Sampling altitude	Peak activity in factors of 100 × background	Hours since burst that peak was encountered	Distance from burst	σ for activity profile	*K*
1951	h	m	ft	ft msl	ft msl			naut mi	naut mi	$(\text{cm}^2\ \text{sec}^{-1} \times 10^{-8})$
Jan 27	13	45	1500–2000	17,000	9,000	28	37.75	1020	45.5	2.6
Jan 28	13	50	1500–2000	35,000	10,000	0.8	28.67	980	52.3	4.6
Feb 2	13	45	1500–2000	35,000	16,000	580	36.5	1030	38	1.9
Feb 2	13	45	1500–2000	35,000	8,000	20	46.25	1300	51	2.7
Feb 6	13	47	1500–2000	40,000	18,000	35	47	1270	44.2	2.0
Feb 6	13	47	1500–2000	40,000	14,000	400	54.5	1270	30.3	0.8
Oct 28	15	20	1100	30,000	25,000	9	33.25	1200	36	1.9
Oct 28	15	20	1100	30,000	18,000	8	28.17	1200	50.7	4.3
Nov 1	15	30	1400	40,000	20,000	1.1	35.25	1710	38	2.0
Nov 19	17	00	0	15,000	14,000	45	47	1760	57.4	3.4
Nov 19	17	00	0	15,000	14,000	21	49.75	1760	59.5	3.4
Nov 19	17	00	0	15,000	14,000	3.5	56	1760	57.5	2.8
Average	. . .		. . .	29,000	15,000	96	40.2	1354	46.7	2.7

each segment had an approximately Gaussian profile out to distances represented by 2σ. The profiles used in Table 1 were very nearly Gaussian-shaped out to at least 3σ, at which point the radioactivity would be only one per cent of the peak.

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Precipitation Scavenging from Atomic Bomb Clouds at Distances of One Thousand to Two Thousand Miles

EUGENE M. WILKINS

Abstract—A convenient rule of thumb is developed for estimating radioactive fallout in precipitation from nuclear clouds at distances of 1000–2000 miles for debris at and below the rain-forming layer. The rule states that rain falling through bomb cloud radioactivity greater than about 100 times background causes deposition activity in excess of 10,000 dpm/ft^2 day. A method is suggested for making a crude estimate of the areal distribution of radioactive rainout which should be applicable under circumstances similar to those in the examples analyzed.

Over the eastern United States, precipitation fell through clouds from the AEC atomic weapons tests of October-November, 1951. This afforded an opportunity to observe the effects of washout from bomb-debris clouds.

Aircraft flights through the clouds at various altitudes up to 25,000 ft msl, combined with the meteorological trajectory analyses, made it possible to delineate approximate areas covered by the clouds while over the eastern United States, and to estimate the regions swept by the clouds during the 24-hour sampling and precipitation collection periods.

Methods and limitations of flight monitoring have been discussed by *Machta* and others [1957], and *List* [1954] has given a comprehensive study of trajectories, fallout predictions and verifications, and discussion of techniques and limitations of ground monitoring in a report on a later weapons test. The main difference for the series discussed here is that collection trays were used in addition to gummed paper for the ground monitoring. Tray collections are expressed in units of disintegrations per minute per square foot per day (dpm/ft^2 day).

Areas swept by each of the debris clouds during a 24-hour period were drawn on a map for altitudes corresponding to 700, 500, and 400 mb. The cloud boundary was arbitrarily defined by a line corresponding to radioactivity approximately 100 times the background level. (The background level for the measurements reported here is of the order of one disintegration per minute per standard cubic meter of air, density = 1.293×10^{-3} gm cm^{-3}). These areas were then compared with maps showing the distribution of 24-hour deposition activity and concurrent precipitation. In this manner it was possible to see how precipitation and cloud position affected the deposition. This method of analysis was applied to three of the bomb clouds in the test series. The following facts were observed:

(1) In all cases where the debris cloud was present below the 500-mb level and precipitation occurred, the tray samples showed deposition of 10,000 dpm/ft^2 day or more.

(2) Presence of the nuclear cloud above the 500-mb level (but not below) and precipitation gave deposition amounts less than 10,000 dpm/ft^2 day, and in most cases the deposition was very small (less than 1,000 dpm/ft^2 day) regardless of the amount of precipitation.

(3) Presence of the cloud below the 500-mb level and no precipitation gave deposition amounts considerably less than 10,000 dpm/ft^2 day. The dry-weather deposition averaged about one-eighth as much as the washout deposition.

Figure 1 is an example for a bomb cloud that passed over the eastern United States on November 1, 1951. Similar results were obtained for the other clouds, but they did not cover so extensive an area. All of these clouds were from air bursts, the fireball not reaching the ground, so that the clouds contained practically no debris other than from the bomb itself.

For these tests, there were only five occurrences of deposition in excess of 100,000 dpm/ft^2 in a 24-hour period. In all five instances, the debris cloud was present (enclosed by the 100-times-background line, which corresponds to air concentration of about 3 dpm/ft^3) at the 700-mb level as well as at the 500-mb level, and 0.10 to 1.21 inches of rain fell during the collection period. The highest reading was 360,000 dpm/ft^2/day, occurring with 0.20 inch of precipitation.

Apparently, if the nuclear cloud is present at or below the rain-forming layer, only a small amount of precipitation is required to accomplish a relatively large amount of scavenging. Otherwise, it is difficult to explain how in some instances neighboring stations receive deposition on the

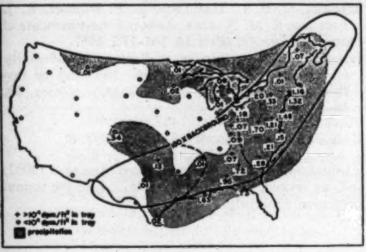

FIG. 1 – Area swept by the section of a nuclear cloud at the 500-mb level on November 1, 1951, in relation to distribution of radioactivity deposited in trays, and concurrent precipitation; the dashed line gives a rough estimate of the cloud position at the beginning and at the end of the sampling period; precipitation amounts are plotted below the station locations, pluses indicating deposition greater than 10,000 dpm/ft² and circles less

same order of magnitude despite a ten-fold greater rainfall at one of the stations.

It is most likely that all of the nuclear debris scavengeable by rain had been removed at the station receiving 1.21 inches of rainfall and a deposition of 260,000 dpm/ft². A station 300 miles away, but beneath the same nuclear cloud, received a deposition of 360,000 dpm/ft² with only 0.20 inch of precipitation. The bomb cloud had spread over so wide an area by this time that concentrations should have been fairly uniform, and the station receiving the lesser deposition was actually nearer the center of the cloud as it passed over. The implication is that the 0.20 inch of precipitation probably was as efficient in scavenging as the 1.21 inches.

This argument is further supported by the scavenging efficiencies computed in Table 1 for the two stations in question. These were made possible by virtue of the fact that the nuclear cloud concentrations (in the portion that subsequently passed into the rain area and over the stations) could be estimated from measurements made in flights through the cloud along the 84th meridian.

The assumption that scavenging occurred from 20,000 ft to the ground cannot be supported by any direct evidence, but it seems to be a reasonable one for these calculations. If it is assumed that a temperature of −12°C to −15°C is needed in the precipitation-forming layer, then the soundings indicate that the precipitation originated at a height of at least 18,000–21,000 ft. Elsewhere, it was observed that precipitation deposition was very light where the cloud was present at the 400-mb level, but not at the 500-mb level, and this suggests that essentially the scavenging occurred from a height between 18,000 and 24,000 ft.

TABLE 1 – *Calculations of scavengeable radioactivity from measurements taken in flights through the nuclear cloud along the 84th meridian on the morning of November 1, 1951*

Altitude	Cpm/30-min filter	Roughly equivalent concentration	Scavengeable activity (assuming an average] between levels)
Station receiving 0.20 inch of precipitation in nine hours			
ft			
20,000	1.5×10^5	47.2 dpm/ft³	24.5×10^4 dpm/ft²
10,000	5.6×10^3	1.8 dpm/ft³	0.9×10^4 dpm/ft²
Surface	(assumed negligible)		
Total scavengeable			2.54×10^5
Total observed			3.6×10^5
Scavenging efficiency			140 pct
Station receiving 1.21 inches of precipitation in nine hours			
20,000	1.9×10^5	59.7 dpm/ft³	30.2×10^4 dpm/ft²
10,000	2.2×10^3	0.7 dpm/ft³	0.35×10^4 dpm/ft²
Surface	(assumed negligible)		
Total scavengeable			3.055×10^5
Total observed			2.6×10^5
Scavenging efficiency			85 pct

These calculations are crude, but they do indicate that, for estimate purposes, it may be assumed that essentially complete scavenging will occur wherever 0.20 inch or more of precipitation falls through the nuclear cloud.

This study does not place an absolute upper limit for washout deposition at distances of one to two thousand miles; on the other hand, the opportunities for scavenging were certainly ideal. Presumably, greater deposition would occur in a situation where the rain-forming layer was higher, providing a greater depth in which scavenging could take place.

The analysis provides a 'rule of thumb' technique for making a crude prediction of precipitation deposition at distances of one to two thousand miles, provided that a forecast can be made of cloud position and precipitation at these distances. The author has shown [*Wilkins*, 1957] that a rough estimate of the lateral distribution of the cloud radioactivity (at various levels) can be obtained for these distances from the classical Fickian Law of diffusion and an 'effective' coefficient of lateral diffusivity, $K = 3 \times 10^8$ cm²/sec.

Acknowledgment—The author is grateful to Lester Machta, K. M. Nagler, and R. J. List for advice in the preparation of this paper. The data used were compiled by those mentioned above and by P. W. Allen, H. L. Hamilton, Jr., and L. F. Hubert of the U. S. Weather Bureau. The research was conducted and reported under the auspices of the U. S. Atomic Energy Commission.

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A Max-Min Dew-Point Hygrometer*

C. B. TANNER AND V. E. SUOMI

Abstract—The lithium chloride Dewcel covered under Foxboro Company patent 2,359,278 has been used in conjunction with a max-min thermometer calibrated directly in degrees dew point to provide maximum and minimum and current dew points. The max-min feature of the hygrometer and the operation convenience make it a particularly suitable instrument for use at cooperative observer stations. A unique advantage of the lithium chloride Dewcel for a cooperating observer station is that the relative error of the measurement is the same at all dew points within the operating range.

First order weather stations collect a large number of hourly and daily meteorological measurements of interest to agriculturists and climatologists. However, the location of many stations on buildings and at airports often impairs the usefulness of the data for agricultural interpretation. In addition the small number of first-order stations limits the spacial sampling. Cooperating-observer stations are located to provide better data for agricultural purposes. In addition there is a far greater number of cooperating-observer stations than first-order stations. However, most cooperating observers collect only 24-hour rainfall and max-min air temperature data. Many other valuable measurements are not made because of the time required for the observer and the expensive equipment involved. Among these measurements are either dew point or relative humidity, net radiation, daytime and nighttime wind distance, and soil temperature. This article describes a simple instrument that provides maximum, minimum, and current dew points that is suitable for use in a cooperative observer station. The instrument is simple to operate and maintain and needs to be read only once a day.

Max-min dew-point hygrometer—The hygrometer assembly is shown in Figure 1. It consists of a Foxboro Dewcel element placed over the stem of a Weston max-min thermometer having a special scale graduated in dew point (°F or °C). A styrofoam shield is placed over the Dewcel element to protect the element from undue heat loss. A polyethylene skirt which drops over the upper end of the styrofoam shield protects the element from driving rain and snow. The hygrometer assembly is mounted in a stainless steel stand that holds the thermometer vertical, but permits the thermometer to be swung to a horizontal position for reading and setting the max-min indexes. A polyethylene cover (not shown) is placed over the thermometer head to shield it from precipitation. The unit is powered with a 25-volt a c, 50 watt transformer with a 50 or 60 watt 110-volt light bulb as ballast in the primary to prevent overloading. A double-wall hygrometer shield for use outside a conventional shelter is shown in Figure 2.

Tests of max-min dew-point hygrometer—The hygrometer was installed in the instrument shelter of the Madison weather station. It was read four times daily at 00 h 30 m, 06 h 30 m, 12 h 30 m, and 18 h 30 m. Psychrometer data were available for comparison at these times. Daily max-min dew points were read at 00 h 30 m and compared to the max-min values obtained by the psychrometer for the previous day. Data were accumulated over 40 days during April–May 1955; 100 days during late October 1955–January 1956; and 150 days during November 1956–April 1957. The data were divided into two classes: when ambient air temperature was above 32°F and below 32°F. The data are presented in Figures 3 and 4. It is to be emphasized that in Figure 3 much of the data nearest to the 1:1 correspondence line lies on previously plotted points.

The spread of data in Figure 3 is small and is accounted for by usual observer errors. Part of the difference is due to the fact that the psychrometer and the dew-point hygrometer have different time constants. Thus short-time fluctuations in dew point are included in the spread of data. The few points with large errors could have arisen from an even five- or ten-degree mistake in reading the hygrometer. Of particular interest in Figure 3 is the trend at low dew points for the psychrometer to read higher than the hygrometer. This trend is likely due to reading the wet bulb before it reached equilibrium.

In Figure 4 when dry-bulb temperatures were below freezing and the wet bulb would be frozen,

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* Contribution from the Department of Soils, University of Wisconsin, Madison, Wisconsin.

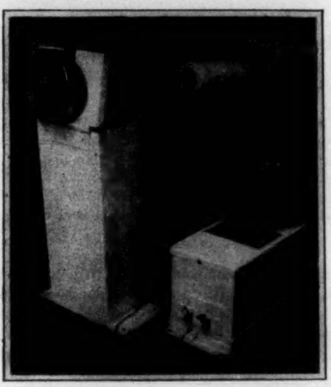

FIG. 1 – Max-min dew-point hygrometer and mounting for weather shelters

the spread of data is considerably greater than in Figure 3. Also evident is a trend for the psychrometer dew points to be lower than hygrometer dew points. This is probably a result of estimating too large a 'wet-bulb' depression. The wet-bulb and dry-bulb thermometers are graduated in even degrees and readings are estimated to 0.1°F. Since a depression is expected, observer bias results in estimating too large a depression. At very low temperatures a depression error of even 0.2°C can effect a large error in dew point. The same error would arise from a fixed error in the psychrometer thermometer calibration.

Characteristics of lithium chloride Dewcel—For each value of vapor pressure or dew-point temperature there exists only one temperature at which a saturated solution of LiCl will be in equilibrium, neither absorbing nor evaporating water. This temperature, conveniently called the LiCl dew point, is plotted against dew point over water in the lower boundary curve in Figure 5. The Foxboro Dewcel, reported by *Hickes* [1947], is a phase cell which is automatically maintained at the LiCl dew point of the ambient air. Thus a measurement of the Dewcel temperature provides the dew point or vapor pressure of the air in which the Dewcel is placed.

The operation and properties of the Dewcel have been discussed by *Hickes* [1947], *Conover* [1950], *Brasefield* [1954], and in detail by *Tanner* and *Suomi* [1956].

The *International Critical Tables* [1928, v. 3, p. 368] indicate that the relation of dew-point temperature to LiCl dew-point temperature is linear over four ranges, each with a different slope, according to the degree of salt hydration. *Brasefield* [1954] carefully calibrated a Dewcel with electronic dew-point equipment and found a linear relationship between dew point and the LiCl dew point over the dew point range −50 to 15°C and found that the data of the International Critical Tables agreed with his experimental data only at dew points above −5°C. *Tanner* and *Suomi* [1956] also found that experimental data and the data of the International Critical Tables agreed at dew points only above 0°C. Unpublished data by Tanner and data here reported confirm Brasefield's results at lower dew points. The FOXBORO COMPANY [1950] published data that indicate a linear relation between dew point and LiCl dew point (the Dewcel characteristic line) over the wide dew-point range of −50 to 45°C.

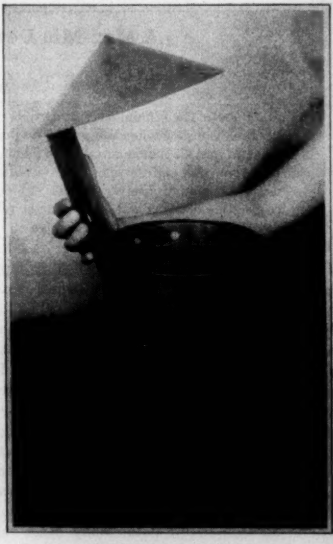

FIG. 2 – Dew-point hygrometer shield for use outside of shelters

Apparently the data of the International Critical Tables are a summary at early static-pressure measurements and are undoubtedly incorrect at dew points less than −10°C. The following equa-

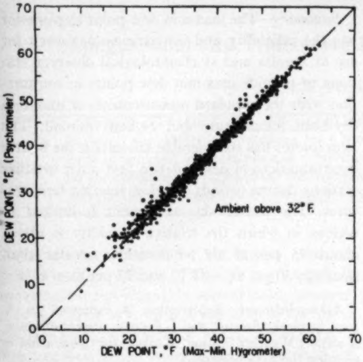

FIG. 3 - Comparison of dew-points from psychrometer and dew-point hygrometer (ambient air temperatures above 32°F)

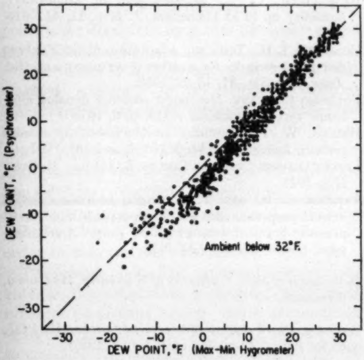

FIG. 4 - Comparison of dew points from psychrometer and dew-point hydrometer (ambient air temperature below 32°F)

tions relating dew point to LiCl dew point provide a good fit with experimental data in the dew-point range of −10 to 40°C.

$$(\text{Dew-point, °C}) = 0.6977\ (\text{LiCl dew point, °C}) - 24.33$$

$$(\text{Dew-point, °F}) = 0.6977\ (\text{LiCl dew point, °F}) - 34.1$$

These same expressions can be used to extrapolate the relation to lower dew points in accordance with Brasefield's findings.

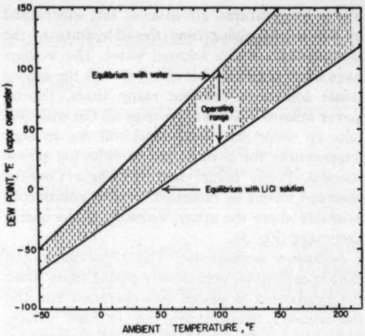

FIG. 5 - Max-min dew-point hygrometer operating range

Dewcel errors—The Dewcel is a heat-balance instrument. At its equilibrium temperature, the power input must equal the conductive, convective, and radiative heat losses. The Dewcel error is proportional to the power input. *Tanner* and *Suomi* [1956] found that the error in an unshielded Dewcel can be as much as 3°C in quiet warm air near saturation. Under these conditions the difference between the Dewcel temperature and ambient dry-bulb temperature is high, thus favoring high convective heat loss. When a Dewcel is exposed to the ventilation of the wind the error can be more serious. Thus heat losses must be minimized and kept as constant as possible by a suitable ventilation and radiation shield. The shield must allow the air sample to change slowly. If these precautions are not taken, large errors will result.

Tanner and *Suomi* [1956] found that the Dewcel reads higher than it should even when the ambient is close to, but not above, the LiCl dew-point. Consequently, the dew point as found from the Dewcel should be 2–3°C (4 to 6°F) above the lower operation boundary of Figure 5. Thus the Dewcel may not be suitable in some arid regions unless the air is refrigerated to the operating range. This is inconvenient.

The Dewcel can indicate dew points higher than those corresponding to saturation. In fogs the water droplets are carried into the Dewcel shield where they evaporate to raise the dew-point. *Conover* [1950] reported high dew point readings (10 to 80°F) when the Dewcel was operated at dew points below 0°F for some time and then rose to higher temperatures. He believes this was caused by the salt changing from the di-hydrate to the mono-hydrate which released water. The authors have never observed this effect, though the appropriate conditions obtained many times. During power failures of even a few minutes the wick will take up water and the Dewcel will rise to high temperatures for a short period following power renewal. Power failure and the effect Conover observed should be indicated by dew points considerably above the upper boundary of the operation range (Fig. 5).

Instrument maintenance—The thermometers can shift in calibration occasionally during times when the hygrometer is placed into operation and the thermometer temperatures rise to high values. This shift is a fixed calibration displacement of a small amount that does not affect the slope of the calibration curve and can be corrected by a suitable dew-point calibration at one and at most two dew points.

The element must be cleaned and recoated with LiCl once every three months. The hygrometer will read high and be sluggish in response if the coating is not renewed. The LiCl film is renewed by washing the old solution free with a jet of distilled water from a wash bottle. Excess water is blotted from the wick and a fresh solution is applied. When power is applied and the wick dries, a uniform white LiCl coating can be seen against the color of the wick. Excess LiCl, evidenced by salt blisters, will cause a sluggish response and may cause a high reading.

The styrofoam shield results in a 95-pct time constant of about 15 min. Thus the hygrometer is insensitive to high-frequency fluctuations in dew point. This is an advantage for most climatic observations.

Summary—The max-min dew-point hygrometer has the reliability and convenience necessary for use at regular and at climatological observer stations to provide max-min dew points in conjunction with the standard measurements of max-min dry-bulb temperature and 24-hour rainfall. The hygrometer has considerable advantage for hourly determinations of dew point in first-order weather stations during periods of below freezing temperatures. The use of the instrument is limited to regions in which the relative humidity is above about 15 pct at air temperatures greater than freezing; 30 pct at −25°F; and 75 pct at −45°F.

Acknowledgment—Appreciation is expressed to A. Joos, formerly director, and J. Rigney, present director, of airport Weather Station, Madison for cooperation in securing the data presented.

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Longitudinal and Transverse Diffusion in Granular Deposits

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Abstract—The pore system of a packed bed is represented by a system of canals in order to permit probability computations for a foreign particle carried by the pore liquid movement to arrive at a certain place in a certain time. The computations lead to explicit values for the coefficient of longitudinal and transversal diffusion. A test device is described which permits the determination of the longitudinal diffusivity. The relationship between test result and theory is discussed.

Introduction—The flow of liquids through porous media is defined by Darcy's law when bulk movement is considered. In several cases, however, it is of interest to know how elements of volume or discrete particles carried by the liquid will travel. For instance, in the study of ground-water movement, radio active salts are injected into the soil. The salt will travel through different pores and after a given interval of time will arrive at different places, their distance from the starting point being dependent upon how tortuous was the path they followed.

This results in a dispersion of the injected salt which is additional to the molecular diffusion. This dispersion caused by the geometry of the pore canal system also has the character of a diffusion with a greater value in the mean direction of flow than perpendicular to this direction. Therefore the two different concepts longitudinal diffusion [*Klinkenberg* and *Sjenitzer*, 1956] and transverse diffusion [*Baron*, 1952] have been introduced in order to indicate this phenomenon.

The passage of the fluid between the grains consists of the summation of a great number of random phenomena, every single phenomenon being represented by the transition from one pore to another. The randomness is originated by the geometry of the pore canals around the grain, which is determined by the adjacent grains whose positions have a random character. This suggests the application of probability calculus in order to obtain an impression of the diffusion coefficients. Many workers have undertaken such probability computations. *Danckwerts* [1953], *Scheidegger* [1954], *Klinkenberg* and *Sjenitzer* [1956] obtain diffusion coefficients by application of probability, without defining the microstructural mechanism of the particle movement. Therefore their result contains a numerical constant, describing the granulometric properties of the porous medium which can only be determined by experiment (tests of *Kramers* and *Alberda* [1953] and *Klinkenberg* and *Sjenitzer* [1956]). Also *Day* [1956] describes such an approach, using the results of *Scheidegger* [1954]. The latter introduces an equal magnitude of transverse and longitudinal diffusion. Tests, however, pointed out that there is a marked difference (6 to 8 times).

In the determination of the diffusion coefficients presented here the starting point is a schematized pore canal system and the movement of the liquid through the canals is accounted for in detail.

Previously, others have applied mechanisms which introduced the grain dimensions (for transverse diffusion, *Baron* [1952]; for longitudinal diffusion, Kramers in a private communication, and *Rifai* and others [1957]). These mechanisms show a probability distribution of discontinuous character, the traveling particle being able to choose only between movements of +1, 0, or −1.

We preferred an approach where the probability distribution is continuous with respect to the direction of the path and proportional to the discharge of all the canals oriented in the direction considered. This approach enables derivation of an expression, which contains both transverse and longitudinal diffusity combined in one formula, and shows the observed difference of the diffusion coefficients in transverse and longitudinal direction.

This result was published by the author [*de Josselin de Jong*, 1956] in Dijon for brevity's sake without detailed mathematical explanation. Because of a regrettable computational mistake and some printing errors the formulas shown there are incorrect; so this article serves as a rectification and a justification of the mathematical treatment.

Notation—The following notation is used.

ℓ length of elementary canal

x, y, z, r coordinates of the exit of an elementary canal, when the entrance is placed in the origin

t residence time for particle in elementary canal

u residence time for elementary canal in principal direction of flow

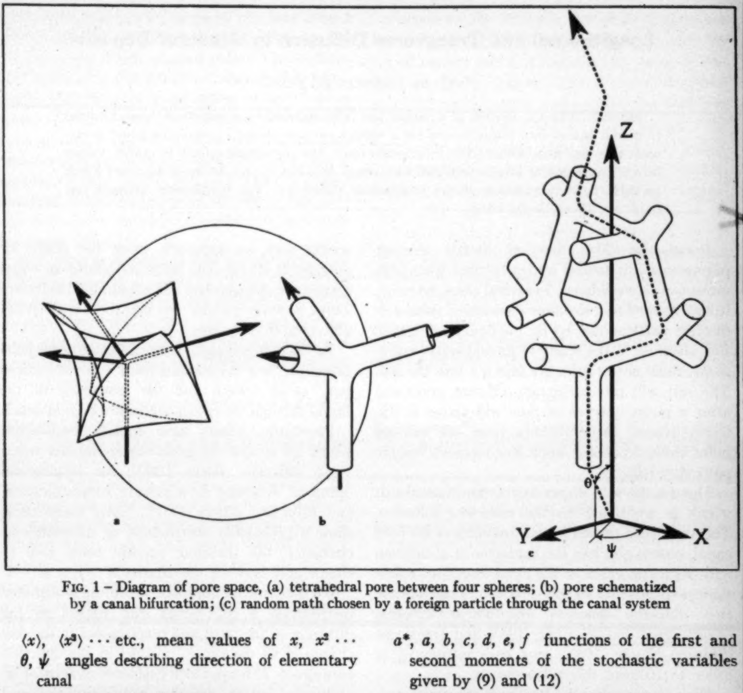

FIG. 1 – Diagram of pore space, (a) tetrahedral pore between four spheres; (b) pore schematized by a canal bifurcation; (c) random path chosen by a foreign particle through the canal system

$\langle x \rangle$, $\langle x^2 \rangle \cdots$ etc., mean values of x, $x^2 \cdots$

θ, ψ angles describing direction of elementary canal

$q_{\theta\psi}$, q_0, Q liquid discharge

v_0 mean velocity of liquid flow

$g_{\theta\psi}$, g_θ, g_ψ distribution functions for choice of paths

P probability function

X, Y, Z, R coordinates of arrival point of a particle, starting in the origin

T time of travel of the particle

N number of canals covered by the particle

X_0, Y_0, Z_0, R_0 coordinates of the maximum number of particles traveling during the time T_0

T_0 arrival time of the maximum number of particles covering a distance Z_0, R_0

N_0 number of canals covered by the maximum number of particles

σ_Z, σ_R, σ_T standard deviations of probability function with respect to Z, R, T

D_Z longitudinal diffusion coefficient

D_R transversal diffusion coefficient

ξ, η, ζ, τ integration variables

a^*, a, b, c, d, e, f functions of the first and second moments of the stochastic variables given by (9) and (12)

A, A', B, C functions given by (15)

λ function of distance Z_0 given by (13) and (23), represented graphically in Fig. 4

$\ln \gamma$ = Euler's constant ≈ 0.577

Schematization of canal system—The pores between grains of spherical form consist of nearly polyhedral cavities connected by triangular shaped canals (Fig. 1a). The resistance to the waterflow is principally determined by the narrow passages, these being oriented at random.

We will schematize this pore system by a network of canals linked together as indicated in Figure 1b. The orientation of the canals is at random, but uniformly distributed in all directions.

We will further suppose that the pressure gradient in each canal is proportional to cos θ, θ being the angle between its direction and the direction of principal flow, Z (Fig. 1c). If for a first approximation the lengths and the conductivity of all elementary canals are taken to be equal, the mean velocity of the liquid in each canal is proportional to $\cos \theta$.

The velocity of flow in the canal varies over its section, so that if a foreign particle moves at a velocity equal to that of the fluid in its immediate vicinity, its velocity will be depended on its radial distance from the center. Brownian motion, however, causes a radial diffusion in the canal [see *van Deemter* and others, 1955], so that if the canal section is small enough we may assume that the velocity of the foreign particle is equal to the mean velocity in the canal.

With these assumptions the residence time t_j in the canal j is given by

$$t_j = u/\cos \theta_j \tag{1}$$

where u is the shortest residence time possible, occurring in a canal oriented in the Z direction. If the length of an elementary canal is ℓ, the distance covered in the x, y, z directions by a canal is

$$x_j = \ell \sin \theta_j \cos \psi_j$$
$$y_j = \ell \sin \theta_j \sin \psi_j \qquad z_j = \ell \cos \theta_j \tag{2}$$

Choice of path—A foreign particle carried by the current through the canals has to choose a new direction of motion every time it arrives at a junction. We will assume that the choice of direction between θ, ψ and $\theta + d\theta, \psi + d\psi$ is distributed in proportion to the quantity of water flowing in these directions taken as a fraction of the total discharge of the canals.

This fraction is computed as follows: From a large number A of canals there are by virtue of the uniform distribution with respect to direction

$$A \sin \theta \, (2\pi)^{-1} \, d\theta \, d\psi \text{ canals}$$

oriented in a direction between θ, ψ and $\theta + d\theta$, $\psi + d\psi$. The discharge of these canals is $q_{\theta\psi} = Aq_0(2\pi)^{-1} \cos \theta \sin \theta \, d\theta \, d\psi$ where q_0 is the discharge of an elementary canal oriented in the Z direction. The total discharge of the A canals is

$$Q = (Aq_0/2\pi) \int_0^{2\pi} d\psi \int_0^{\pi/2} \sin \theta \cos \theta \, d\theta = \frac{1}{2} Aq_0$$

So the fraction of discharge in the $\theta \rightarrow \theta + d\theta$, $\psi \rightarrow \psi + d\psi$ direction is

$$g_{\theta\psi} d\theta \, d\psi = q_{\theta\psi}/Q = \pi^{-1} \cos \theta \sin \theta \, d\theta \, d\psi \tag{3}$$

The path followed by the particle is determined by the subsequent choices, each being distributed according to the distribution function $g_{\theta\psi}$.

In order to show the scattering effect let us consider how far a particle is deviated when it follows a canal in direction θ, ψ for a time Δt ($<u$). The velocity in this canal is $(\ell/u) \cos \theta$, so that the deviations Δz and Δr are

$$\Delta z = \Delta t \cdot (\ell/u) \cos^2 \theta = \tfrac{1}{2}(\Delta t \cdot \ell/u)(1 + \cos 2\theta)$$

$$\Delta r = \Delta t \cdot (\ell/u) \sin \theta \cos \theta = \tfrac{1}{2}(\Delta t \cdot \ell/u) \sin 2\theta$$

These deviations lie on a sphere with radius $\Delta t \cdot \ell/2u$ and center at $z = \Delta t \cdot \ell/2u$. The distribution function $g_{\theta\psi} = (2\pi)^{-1} \tfrac{1}{2} \sin 2\theta \, d(2\theta) \, d\psi$ also shows that the arrival points on the sphere are uniformly distributed over its surface. This scattering therefore bears a resemblance to Brownian motion super-imposed on a translation, and the problem has become one of random flight. However, there is a difference in that the residence time in the free paths for Brownian motion is independent of the orientation. For the problem considered here, the residence time is inversely proportional to $\cos \theta$, so that its value is infinite in the extreme case $\theta = \pi/2$.

For the determination of the diffusion coefficient we can, with some alterations, make use of the probability calculus developed for Brownian motion [*Chandrasekhar*, 1943, pp. 8–16].

Introduction of probability—When the particle has passed through a large number, N, of canals, it has arrived at a point X, Y, Z where

$$\left.\begin{aligned} X &= \sum x_j = \sum \ell \sin \theta_j \cos \psi_j \\ Y &= \sum y_j = \sum \ell \sin \theta_j \sin \psi_j \\ Z &= \sum z_j = \sum \ell \cos \theta_j \end{aligned}\right\} \tag{4}$$

The summation being from $j = 1$ to N. The time of travel is

$$T = \sum t_j = \sum u/\cos \theta_j \tag{5}$$

With the aid of Markoffs theorem [*Chandrasekhar*, 1943, p. 9] we can determine the probability $P_N(X, Y, Z, T) \, dX \cdot dY \cdot dZ \cdot dT$, that the particle after N passages has arrived in the volume between (X, Y, Z) and $(X + dX, Y + dY, Z + dZ)$ during the time interval T to $T + dT$, as

$$P_N(X, Y, Z, T) \, dX \, dY \, dZ \, dT$$
$$= \frac{dX \, dY \, dZ \, dT}{(2\pi)^4} \int_{-\infty}^{+\infty} d\xi \int_{-\infty}^{+\infty} d\eta \int_{-\infty}^{+\infty} d\zeta \int_{-\infty}^{+\infty} d\tau$$
$$\times \exp \{-i(\xi X + \eta Y + \zeta Z + \tau T)\} \times A_N \tag{6}$$

where

$$A_N = \left[\int_0^{\pi/2} d\theta \int_0^{2\pi} d\psi \, g_{\theta\psi} \right.$$
$$\left. \cdot \exp \{+i(\xi x_j + \eta y_j + \zeta z_j + \tau t_j)\} \right]^N$$

By introduction of T as the fourth component of the vector whose probability is determined, the dependence of the residence times on the stochastic variables is accounted for. The result P_N, however, is not yet sufficient because the particle may arrive at X, Y, Z in a time T in different ways with different numbers of passages N. For instance, the particle may choose a path which, being oriented in the z direction, brings it quickly very near to XYZ and then take a canal nearly perpendicular to Z with such a long residence time that the rest of T is consumed there. In that case the number of choices, is very small in comparison to the mean number of passages necessary. It is therefore necessary to integrate P_N over all possible values of N to obtain the required probability.

$$P(X, Y, Z, T) = \int_{N_1}^{N_2} P_N(X, Y, Z, T, N)\, dN \quad (7)$$

For points on the Z axis ($X = Y = 0$) the extreme values for N are $N_1 = Z/\ell$ and $N_2 = (ZT/u\ell)^{\frac{1}{2}}$.

Standard deviations—The probability distribution $P(X, Y, Z, T)$ for the arrival of one particle is a measure for the concentration distribution when a great number of particles is injected.

The dispersion may be described by diffusion coefficients which according to Einstein equa

$$D = \sigma^2/2T \quad (8)$$

where σ is the standard deviation of the probability distribution. As $P(X, Y, Z, T)$ is a function of X, Y, Z, and T we may derive for a given T, the place X, Y, Z where the probability is a maximum, and the standard deviation σ_X, σ_Y, σ_Z in the directions perpendicular and parallel to the principal stream around this maximum. But also we can take a fixed point in space and determine the standard deviation σ_T describing the changes of concentration in course of time at the moment when the maximum concentration passes.

In order to determine these standard deviations from the probability described by (6), several integrations have to be executed.

Integration of the expression for the probability—First the value of A_N has to be determined, which may be effected in a way similar to that shown by *Chandrasekhar* [1943]. We encounter here, however, the difficulty that t_j becomes infinite for $\theta = \pi/2$ according to (1).

We will not enter into the mathematical details, which can be obtained by request to the author, but infer, that to the neglect of small terms for $N \gg 1$, the following result is obtained.

$$A_N = \exp \{N[i\tau d + i\zeta e - (a^*\tau^2 + 2b\tau\zeta + c\zeta^2 + f\xi^2 + f\eta^2)]\} \quad (9)$$

with

$$a^* = [\ln (i/\gamma\tau u) - \tfrac{1}{2}]u^2$$
$$b = \tfrac{1}{2}[\langle tz\rangle - \langle t\rangle\langle z\rangle] = -u\ell/6$$
$$c = \tfrac{1}{2}[\langle z^2\rangle - \langle z\rangle^2] = +\ell^2/36$$
$$d = \langle t\rangle = 2u \qquad e = \langle z\rangle = 2\ell/3$$
$$\langle x\rangle = \langle y\rangle = \langle r\rangle = 0$$
$$f = \tfrac{1}{2}\langle x^2\rangle = \tfrac{1}{2}\langle y^2\rangle = \tfrac{1}{2}\langle r^2\rangle = \ell^2/8$$

where ⟨ ⟩ indicates the mean value.

Introduction of this value for A_N into (6) for P_N shows that next integrations versus τ, ζ, ξ, and η have to be executed. With respect to ζ, ξ and η this is readily performed by the use of the well known result

$$\int_{-\infty}^{+\infty} \exp (i\mu\alpha - \mu^2\beta^2)\, d\mu = \pi^{\frac{1}{2}} \beta^{-1} \exp (-\alpha^2/4\beta^2) \quad (10)$$

For the ξ, η part of the integral this gives, using polar coordinates, a result which yields the probability, that the particle should arrive in the ring between R and $R + dR$

$$(2\pi R\, dR/4\pi Nf) \;\exp\{-R^2/4Nf\} \quad (11)$$

From the τ, ζ part of the integral only the integration versus ζ may be treated according to (10) giving

$$(2\pi)^{-2}\, dT\, dZ(\pi/cN)^{\frac{1}{2}} \int_{-\infty}^{+\infty} d\tau \times \exp \{- i\tau[T - dN] + i(b/c)\tau[Z - eN] - ([Z - eN]^2/4cN) - N\tau^2[a^* - (b^2/c)]\}$$

The subsequent integration with respect to τ shows the difficulty that a^* is a function of τ. Here again we cannot extend upon the mathematical details, (which can be obtained by request) by which may be proved that a very good approximation is obtained by substitution of the constant a instead of a^* according to

$$a = (\lambda - \tfrac{1}{2} - \ln \gamma)u^2 \quad (12)$$

with λ the root of

$$N = \tfrac{1}{2}e^{2\lambda}/(\lambda - \tfrac{1}{2} - \ln \gamma) \quad (13)$$

The relationship between λ and N according to (13) is represented in Figure 2. Again the larger N, the better the approximation. With this substitution, the coefficient of τ^2 in the integrant is independent of τ, and (10) may be used. Then finally the following result is obtained for P_N.

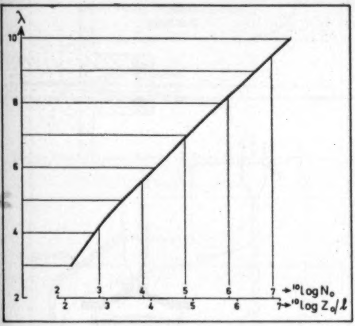

FIG. 2 – Graphical representation of Eq. 13 combined with Eq. 21; λ as a function of Z_0 the distance of the maximum concentration, and ℓ the elementary canal length

$$P_N(T, Z, R)\, dT\, dZ\, dR = (dT\, dZ\, R\, dR/8\pi N^2 f(ac - b^2)^{\frac{1}{2}})$$
$$\times \exp\{-(A + A')N^{-1} + B - CN\} \quad (14)$$

wherein

$$\left.\begin{aligned} A &= [cT^2 - 2bTZ + aZ^2]/4(ac - b^2) \\ B &= 2[cdT - b(eT + dZ) + aeZ]/4(ac - b^2) \\ C &= [cd^2 - 2b\, de + ae^2]/4(ac - b^2) \\ A' &= R^2/4f \end{aligned}\right\} \quad (15)$$

In order to obtain the diffusion coefficients as the final result of our considerations, the subsequent treatment of (14) for the probability P_N, that a particle after N choices arrives at a point Z, R in a time T, involves an integration with respect to N, and the determination of the standard deviations with respect to Z, R, or T. These operations become easy to perform if it is realized that according to the central-limit theorem the different probabilities involved will approach a normal law for $N \gg 1$. Therefore, if a result is obtained for the probability distribution of a variable μ given by

$$P(\mu)\, d\mu = \exp\{F(\mu)\}\, d\mu$$

we can replace the function F of μ in the exponent by

$$F(\mu) = F(\mu_0) + \tfrac{1}{2}(\mu - \mu_0)^2 F''(\mu_0) \quad (16)$$

where μ_0 is the value of μ for which $F(\mu)$ has its maximum. Because the distribution of $P(\mu)$ is approximately normal the higher order terms in the Taylor expansion of $F(\mu)$ may be neglected. From (16) it is obvious that the standard deviation of $P(\mu)$ approaches the value

$$\sigma_\mu = [-F''(\mu_0)]^{\frac{1}{2}} \quad (17)$$

The evaluation of an integral of the form

$$\int_{\mu_1}^{\mu_2} P(\mu)\, d\mu = \int_{\mu_1}^{\mu_2} \exp\{F(\mu)\}\, d\mu$$

can by virtue of the substitution (16) be approximated by

$$\int_{-\infty}^{+\infty} \exp\{F(\mu_0) - \tfrac{1}{2}[-F''(\mu_0)](\mu - \mu_0)^2\}\, d(\mu - \mu_0)$$
$$= [2\pi/ - F''(\mu_0)]^{\frac{1}{2}} \exp\{F(\mu_0)\} \quad (18)$$

The error introduced by the additional integrals over the intervals $-\infty \to \mu_1$ and $\mu_2 \to +\infty$ is negligible if the integrand in these intervals consists of an exponential of large negative value. In the case of the integration with respect to N, which has to be performed on (14) according to (7), the values of N_1, N_2, and $F(N)$ are such that in agreement with this condition the extension of the boundaries to $+\infty$ and $-\infty$ is permissible. Therefore the result of the integration versus N can be obtained by determining the value of N_0 for which $F(N)$ in (16) is a maximum and subsequently $F''(N_0)$. These determinations necessitate only differentiations on $F(N)$ being operations which are always feasible. Neglecting terms of small order, there results

$$N_0 = [(A + A')/C)^{\frac{1}{2}} \qquad \sigma = [N_0/C]^{\frac{1}{2}} \quad (19)$$

and the probability for the particle to arrive in time T at a point with coordinates Z, R is

$$P(T, Z, R)\, dT\, dZ\, dR = \frac{dT\, dZ\, R dR}{8f[\pi(ac - b^2)]^{\frac{1}{2}}} \left[\frac{C}{(A + A')^3}\right]^{\frac{1}{2}}$$
$$\times \exp\{B - 2[1 + C(A + A')]^{\frac{1}{2}}\} \quad (20)$$

wherein A, A', B, C are given by (15) and a, b, c, d, e, f by (9) and (12).

Character of the probability $P(T, Z, R)$—From (20) for the probability several conclusions may be drawn with respect to standard deviations. The expression is a function of T, Z and R because the factors A, A' and B contain them. The maximum of $P(T, Z, R)$ lies in T_0, Z_0, R_0 given by

$$T_0 = dZ_0/e = 3uZ_0/\ell \qquad R_0 = 0 \quad (21)$$

This means that the maximum concentration of an injected substance travels at a velocity v_0 equal to the mean velocity $\langle z\rangle/\langle t\rangle = \frac{1}{3}\ell/u$. That the maximum also follows the axis $R = 0$ is evident.

The standard deviations about the maximum may be derived with (17). We obtain then

$$\left.\begin{aligned}
\sigma_R &= [2Z_0f/e]^{\frac{1}{2}} = [Z_0\langle r^2\rangle/\langle z\rangle]^{\frac{1}{2}} = \ell[3Z_0/8\ell]^{\frac{1}{2}}\\
\sigma_T &= [2Z_0(cd^2 - 2bde + ae^2)/e^3]^{\frac{1}{2}}\\
&= [Z_0(\langle z^2\rangle\langle t\rangle^2 - 2\langle zt\rangle\langle z\rangle\langle t\rangle\\
&\quad + \tfrac{1}{2}(\lambda + \tfrac{3}{2} - \ln\gamma)u^2\langle z\rangle^3)/\langle z\rangle^3]^{\frac{1}{2}}\\
{}_T &= u[3Z_0(\lambda + \tfrac{3}{4} - \ln\gamma)/\ell]^{\frac{1}{2}}\\
\sigma_Z &= (e/d)\sigma_T = \tfrac{1}{3}\,\ell[3Z_0(\lambda + \tfrac{3}{4} - \ln\gamma)/\ell]^{\frac{1}{2}}
\end{aligned}\right\}\quad(22)$$

In these expressions Z_0 is the distance along the z axis, where the maximum is at the moment T_0. The maximum number of choices N_0 for the maximum at Z_0 is given according to (19) by

$$N_0 = Z_0/e = 3Z_0/2\ell \qquad (23)$$

The length of ℓ is given by the geometry of the pore canal system, while λ can be read from Figure 2 as a function of N_0 or computed by (13).

The standard deviation σ_T applies to the change of concentration registered at a point on the axis when the maximum passes by. The approximated value of σ_T as given in (22) is applicable for the case of a point injection as well as for the breakthrough curve of a plane front. Exact computation of these two different cases from (20) would yield a slightly different result.

The standard deviations σ_R and σ_Z represent the dispersion of a point injection in longitudinal and transverse directions at a certain moment. From these values the diffusion coefficients D_R and D_Z may be computed by (8) and give

$$\left.\begin{aligned}
D_R &= \sigma_R^2/2T_0 = 3\,v_0\ell/16\\
D_Z &= \sigma_Z^2/2T_0 = v_0\ell(\lambda + \tfrac{3}{4} - \ln\gamma)/6
\end{aligned}\right\}\quad(24)$$

From this result we deduce that the interrelation between these diffusion coefficients is

$$D_Z/D_R = 8(\lambda + \tfrac{3}{4} - \ln\gamma)/9 \qquad (25)$$

which according to (13) is dependent on the distance, since λ is a function of N_0 and $N_0 = 3\,Z_0/2\ell$. The order of magnitude of D_Z/D_R would be 6.5 for $N_0 = 10^5$.

In the foregoing computations ℓ the length of the elementary canals was invariable. The introduction of a statistically distributed canal length in the given analysis, entails no essential difficulties. We did not represent its influence because we assumed that for the example given by the experiment this influence was small in comparison to the scattering effect produced by the orientation of the canals.

Experiments—Several experiments have been run with the percolation apparatus represented diagrammatically in Figure 3. The cylinder (φ 6 cm, height 20 cm) was packed with glass spheres of 0.2 mm diameter (standard deviation 0.05 mm). The packing was carefully controlled to procure a uniform porosity of 38.5 volume pct.

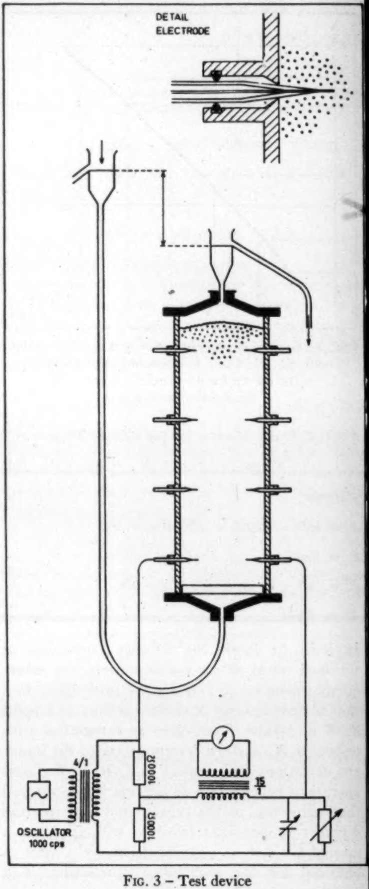

FIG. 3 – Test device

The system was saturated with distilled water with NaCl to a concentration of 0.02 normal. The liquid under the filter was replaced by water with a 1.0 normal NaCl concentration. Next the waterflow was started at a filter velocity upwards of

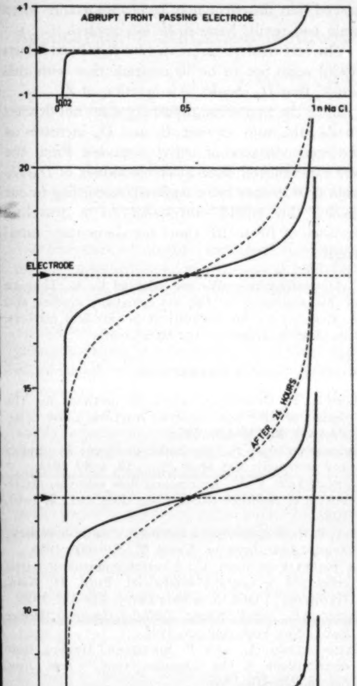

FIG. 4 – Salinity as registered by electrodes

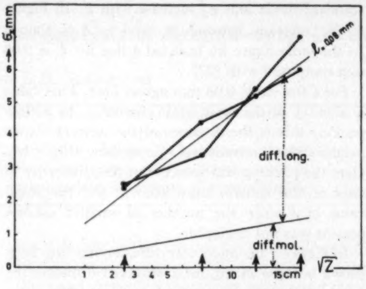

FIG. 5 – Observed standard deviations as related to theory

6 cm³/minute. The mean velocity through the pores $\langle z \rangle / \langle t \rangle$ was

$$(6/\tfrac{1}{4}\pi 6^2) \times (1/0.385) = 0.55 \text{ cm/min}$$

At different distances from the bottom (2.5, 7.5, 12.5, 17.5 cm) electrodes were inserted into the grain material, and permitted salinity measurements of the interstitial liquid. The electrodes consisted of a platinum wire ϕ 0.7 mm, length 3 mm and were covered with platinum-black. The electrical specific resistance of the material around these electrodes was determined with the Wheatestone bridge (1000 cps, 50 μA) represented diagrammatically in Figure 3. Calibration in different NaCl concentrations gave the relation between salinity and electric resistance in the circuit. Calibration in the liquid alone as well as after introduction of the grains gave values which correspond with theoretical computations based on potential distribution around ellipsoids and reduction of conductivity by the grain material. By measuring the resistivity variations with respect to time the break-through curve as the saline front passed by, could be determined.

In Figure 4 is given the salinity as registered by the electrodes at the moment that a particle traveling at the mean velocity would have arrived at the distance indicated by the abscissa. The error introduced by the finite dimension of the electrodes is shown by the curve at the top of Fig. 4 where, based on theoretical calculations of the potential distribution round ellipsoids, the apparent concentration variations measured by an electrode have been drawn for the passing of an abrupt front.

The observed curves show a distribution that is nearly normal. Their inclination increases with the distance from the bottom indicating that also the standard deviations σ_z increase with Z. In Figure 5 the relation between σ_z and $\sqrt{Z}$ is shown. In the same figure we inserted a line for $\ell = 0.08$ mm computed with (22).

For ℓ the value 0.08 mm agrees best. This value is about ⅓ of the main grain diameter. In a close packing this is the distance of the centers of two neighbouring tetrahedral pores (see Fig. 1a). Here the packing was looser, but the difference in sizes of the spheres may account for the small value of ℓ since the number of smaller spheres present was not negligible.

In Figure 5 the molecular diffusion has also been shown because in the total observed diffusion the effect of Brownian motion is present. Molecular diffusion was determined in the percolation apparatus as follows.

The percolation test was executed as above for the front passing the two lower electrodes. Then the liquid flow was stopped during 24 hours and started again in order to let the front pass the two upper electrodes. The additional inclination of the break-through curves correspond to an acceptable diffusion coefficient of

$$D_m = 0.7 \times 10^{-5} \text{ cm}^2/\text{sec}.$$

The normal runs lasted about 30 minutes, so the influence of molecular diffusion was not sufficient to affect the interpretation of the test results (see Fig. 5).

Conclusions—The introduction of a continuous probability distribution for the random choice of travel direction at a bifurcation in the pore canal system permits the computation of longitudinal and transversal diffusion from a formula which contains both together as a probability expression (20). Both diffusion coefficients are proportional to the mean velocity, as has previously been found by several other workers in this field. Further they are proportional to ℓ which is of the order of the grain size, but depends on the grain-size distributions and packing. In the glass beads packing investigated ℓ amounted to about ⅓ of the mean diameter of the grains.

The longitudinal diffusion coefficient moreover depends on the distance Z_0, which has been covered by the particle traveling at the mean velocity. This dependence is nearly proportional to $\ln \sqrt{Z_0}$. In experiments, where Z_0 varies over a small range this dependence will remain unobserved, but the effect may be of importance when scale test results have to be interpreted.

The test results represented by *Rifai* and others [1956] seem not to be in contradiction with this result, that D_Z should be a function of Z_0.

Since the transverse diffusivity does not depend on Z_0, the ratio between D_Z and D_R increases as the mean distance of travel increases. From the few experimental data available values of D_Z/D_R from 6 to 10 have been reported. According to our theory this would correspond to a traveling distance of 10^5 to 10^8 times the elementary canal length.

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Application of Statistical Methods to the Analysis of Ground-water Levels

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Abstract—Valuable hydrologic information can be obtained from statistical analysis of water-level trends. The time-series and the functional-equation approaches are applied to New Jersey well records representing different hydrologic conditions. The results are valuable as concise summaries of the records, for extrapolating observed data, for interpolating between measurements, and for estimating hydrologic factors such as coefficients of transmissibility and storage, evapotranspiration, and ground-water discharge.

Introduction—Valuable hydrologic information can be obtained from the statistical analysis of ground-water level trends. Such analysis can separate and define the factors responsible for the water-level movements. It can be used to interpolate between measurements or predict future water levels under given conditions. Numerical expressions can be derived that concisely summarize the record. Finally, this approach helps to clarify important hydrologic factors such as coefficients of transmissibility and storage, evapotranspiration, and ground-water discharge.

Two types of statistical analysis are applied in this paper to records of water-levels. One method analyzes them as time series and separated the secular (long-term), annual, cyclical, and irregular trends. Its primary purpose "is to discover and measure any irregularities which characterize the movement of the data through time" [*Neiswanger*, 1948, p. 475]. The other method derives functional relationships between water levels and other hydrologic factors. Some data are suited to the time-series approach, some to the functional approach, and some to a combination of both.

Water-level records from three different areas in New Jersey are analyzed to show the applicability of the methods to different hydrologic conditions. Water-level trends in the well at Longport are affected most by artificial ground-water withdrawals. Data from a water-spreading area near Seabrook illustrate the effects of artificial ground-water recharge. Water-level trends in the Hulsart well near Old Bridge reflect climatic and other natural conditions. For the Seabrook analysis, measurements from a dense network of observation wells were used, whereas for the Hulsart and Longport analysis, measurements from single wells were used.

Analysis of water-level trends in the well at Longport, N. J.—The Longport (14th Avenue) well, located along the coast of New Jersey, reflects water levels in the aquifer known locally as the 800-foot sand. Longport, Margate City, Ventnor City, and Atlantic City to the north, and Ocean City to the south, draw substantial quantities of water from this confined aquifer [*Thompson*, 1928; *Barksdale*, *Sundstrom* and *Brunstein*, 1936].

Figure 1 and column 2 in Table 1 show the monthly median water levels in the Longport well, below an arbitrarily chosen datum, for the period from 1925, the first year of complete record, through 1952. The datum is the median water-level altitude of January 1925, 15.0 ft below mean sea level. The seasonal fluctuations result largely from the seasonal changes in pumping rates. The general water-level decline from 1925 until 1929, the slight recovery beginning with 1930, and the marked decline since 1944 correlate with changes in rates of pumping from the aquifer.

Figure 1 shows clearly defined secular (long-term) and annual (seasonal) variations. Therefore, it is well suited to the time-series type of analysis. Of the several time-series methods available, the ratio-to-trend method [*Arkin* and *Colton*, 1950, pp. 67–75] was used to separate and clarify the most prominent individual trends in the record.

The first step in the application of the ratio-to-trend method is the determination of the long-term or secular behavior of the data. Because of the distribution of the data, this was done by fitting the following to the hydrograph

$$s = K_1 + K_2 \log_e t \qquad (1)$$

where s = the drawdown of the water level in the Longport well below the datum, ft

t = the elapsed time since datum period of January 1925, days

K_1 and K_2 = constants

Eq. (1) was fitted to the Longport data by

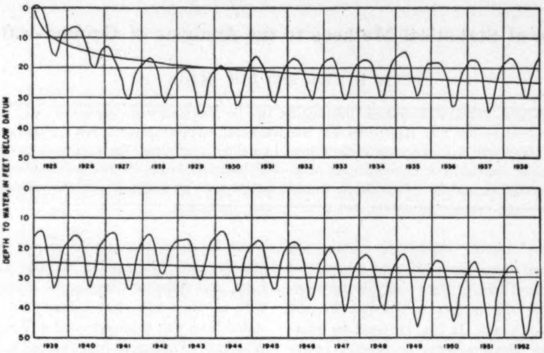

FIG. 1 – Hydrograph of the 14th Avenue well, Longport, N. J., with the long-term trend line superposed

applying the principle of least squares. The sum of the squares of the deviations of the observed values about the trend line computed by this method is a minimum. The least-squares line was determined from the 'normal' forms of (1) [*Arkin* and *Colton*, 1950, pp. 210–211].

$$\sum s = NK_1 + K_2 \sum \log_e t$$

$$\sum (s \log_e t) = K_1 \sum \log_e t + K_2 \sum (\log_e t)^2 \quad (2)$$

where N is the number of items in the set of data to which the equations are applied.

Using yearly mean values of drawdown s and time t for 1925 through 1952, the solution of the normal equations is

$$K_1 = -14.68 \text{ and } K_2 = 4.65$$

Substituting these values in (1), the long-term trend equation for the Longport well becomes

$$s = -14.68 + 4.65 \log_e t \quad (3)$$

A trend line based on (3) is plotted on the Longport hydrograph, Figure 1. It shows the trend values of s, the computed position of the water table below the datum. Each trend value of s, listed in column 4 of Table 1, corresponds to an actual median water-level position below the datum (Table 1, column 2). The following steps analyze the differences between the actual and trend values of s.

In the second step of the analysis, the ratio of each observed value of s to its respective computed trend value was listed in column 5 of Table 1. The departures of the ratios from unity measure the deviations of the observed water levels from the computed long-term trend values. Column 5 shows that the July 1925 drawdown, for example, was 23 pct greater than its respective trend value, and the December 1925 drawdown was 37 pct less than its respective trend value.

In the third step, the ratios were averaged by months after extreme values were eliminated by means of a multiple-frequency table [*Arkin* and *Colton*, 1950, p. 71]. The resulting monthly average indices of variation (seasonal indices), column 6, Table 1, show the typical position of the water level for each month relative to the trend position. For example, January drawdowns average 18 pct less than the trend values, and July drawdowns average 24 pct greater than the trend values.

In the fourth step, the respective monthly indices of variation were subtracted from the individual monthly ratios in column 5. This removed the average monthly variations from the data. The resulting values in column 7 represent the cyclical and irregular deviations remaining in the data after the secular and seasonal trends have been removed.

In the final step of the analysis, the data were smoothed by means of a 12-month centered moving average [*Arkin* and *Colton*, 1950, pp. 46–49]. This removed the irregular variations and isolated the cyclical variations, listed in column 8 of Table 1. Since 1947, a cycle has been in progress during which water-level drawdowns have been greater than the combined trend and annual values. Table 1 shows that the cyclical water-level drawdowns

TABLE 1 – *Application of the ratio-to-trend method to the Longport well data*

Year and month 1	Median position of water table, below datum 2	Time since datum month 3	Computed value of s, below datum 4	Ratio of observed to trend value of s 5	Monthly index 6	Cyclical and irregular values 7	Cyclical values 8
1925	ft	day	ft				
Jan.	0.0	0			0.82		
Feb.	−0.3[a]	30	1.12	−0.27	0.77	−1.04	...
Mar.	−0.2	59	4.32	−0.05	0.75	−0.80	...
Apr.	0.5	90	6.23	0.08	0.74	−0.66	...
May	2.2	120	7.58	0.29	0.83	−0.54	...
June	6.2	151	8.62	0.72	1.00	−0.28	...
July	11.6	181	9.46	1.23	1.24	−0.01	−0.35
Aug.	15.8	212	10.20	1.55	1.42	0.13	−0.29
Sep.	16.3	243	10.82	1.51	1.39	0.12	−0.23
Oct.	12.6	273	11.37	1.11	1.19	−0.08	−0.19
Nov.	9.2	304	11.88	0.77	1.00	−0.23	−0.17
Dec.	7.8	334	12.30	0.63	0.89	−0.26	−0.16
1926							
Jan.	7.8	365	12.72	0.61	0.82	−0.21	−0.19
Feb.	7.0	395	13.07	0.54	0.77	−0.23	−0.23
Mar.	6.7	424	13.48	0.50	0.75	−0.25	−0.26
Apr.	6.8	455	13.76	0.49	0.74	−0.25	−0.26
May	7.1	485	14.02	0.51	0.83	−0.32	−0.23
June	8.4	516	14.35	0 59	1.00	−0.41	−0.21
July	11.1	546	14.60	0.76	1.24	−0.48	−0.19
Aug.	15.4	577	14.81	1.04	1.42	−0.38	−0.17
Sep.	19.8	608	15.09	1.31	1.39	−0.08	−0.14
Oct.	20.2	638	15.30	1.32	1.19	0.13	−0.10
Nov.	17.1	669	15.52	1.10	1.00	0.10	−0.05
Dec.	14.6	699	15.70	0.93	0.89	0.04	−0.03
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
1937							
Jan.	18.7	4383	24.3	0.77	0.82	−0.05	−0.05
Feb.	17.6	4413	24.3	0.72	0.77	−0.05	−0.04
Mar.	17.5	4442	24.4	0.72	0.75	−0.03	−0.04
Apr.	17.8	4473	24.4	0.73	0.74	−0.01	−0.04
May	19.6	4503	24.4	0.80	0.83	−0.03	−0.03
June	23.4	4534	24.5	0.96	1.00	−0.04	−0.03
July	29.6	4564	24.5	1.21	1.24	−0.03	−0.03
Aug.	35.0	4595	24.5	1.43	1.42	0.01	−0.03
Sep.	33.0	4626	24.6	1.34	1.39	−0.05	−0.03
Oct.	27.8	4656	24.6	1.23	1.19	0.04	−0.03
Nov.	23.2	4687	24.6	0.94	1.00	−0.06	−0.04
Dec.	20.6	4717	24.6	0.84	0.89	−0.05	−0.05
.	.	.	.	.	.	.	.
.	.	.	.	.	.	.	.
1952							
Jan.	28.4	9861	28.1	1.01	0.82	0.19	0.23
Feb.	27.0	9891	28.1	0.96	0.77	0.19	0.24
Mar.	26.0	9920	28.1	0.93	0.75	0.18	0.24
Apr.	26.6	9951	28.1	0.95	0.74	0.21	0.24
May	28.6	9981	28.1	1.02	0.83	0.19	0.24
June	36.5	10012	28.2	1.29	1.00	0.29	0.24
July	45.4	10042	28.2	1.61	1.24	0.37	...
Aug.	49.4	10073	28.2	1.75	1.42	0.33	...
Sep.	47.0	10104	28.2	1.67	1.39	0.28	...
Oct.	40.0	10134	28.2	1.42	1.19	0.23	...
Nov.	34.6	10165	28.2	1.23	1.00	0.23	...
Dec.	31.2	10195	28.2	1.06	0.89	0.17	...

[a] Negative values in column 2 correspond to water-level altitudes above the datum.

TABLE 2 – *Predicted and observed water-level drawdowns in the Longport well*

Year and month 1	Time since datum month 2	Computed trend value, s 3	Monthly index 4	Cyclical and irregular deviations 5	Total index 6	Predicted water-level drawdown 7	Observed water-level drawdown 8
1953	day						
Jan.	10,226	28.3	0.82	0.21	1.03	29.2	29.2
Feb.	10,256	28.3	0.77	0.21	0.98	27.7	27.9
Mar.	10,284	28.3	0.75	0.20	0.95	26.9	27.5
Apr.	10,315	28.3	0.74	0.23	0.97	27.5	28.1
May	10,345	28.3	0.83	0.22	1.05	29.7	29.3
June	10,376	28.3	1.00	0.32	1.32	37.3	36.0
July	10,406	28.3	1.24	0.40	1.64	46.4	47.6
Aug.	10,437	28.3	1.42	0.36	1.78	50.4	52.8
Sep.	10,468	28.3	1.39	0.31	1.70	48.1	52.2
Oct.	10,498	28.3	1.19	0.27	1.46	41.3	43.6
Nov.	10,529	28.4	1.00	0.27	1.27	36.1	37.0
Dec.	10,559	28.4	0.89	0.21	1.10	31.2	33.4

were 24 pct of the trend values in the first part of 1952.

In summary, the time-series analysis of the Longport hydrograph yielded: (1) The trend equation: $s = -14.68 + 4.65 \log_e t$; (2) monthly indices (Table 1, column 6); and (3) cyclical and irregular deviations for 1952 (Table 1, column 7).

The deviations of the actual monthly indices from the average monthly indices were larger during the summer of 1952 than during the rest of the year. Such unanalyzed deviations are included in the cyclical and irregular deviations. Therefore, the cyclical and irregular deviations rather than the cyclical deviations alone were included in the summary of Longport well data shown above.

The results of the time-series analysis were used to predict water-level drawdowns for 1953, as shown in Table 2. It was assumed that the secular and annual (seasonal) trends would continue, that the irregular deviations for 1953 would be the same as those computed for 1952, and that the cyclical deviations would increase at the rate of one per cent of the trend values every five months. Eq. 3 was used to determine the secular-trend values in column 3 of Table 2. The 1952 cyclical and irregular deviations, having been increased at the rate of one per cent every five months (col. 5), were added to the monthly indices (col. 4) to give total indices (col. 6). The secular trend values were finally multiplied by the total indices to give the predicted water levels below datum (col. 7). Comparison with the observed drawdowns in column 8 shows that no large changes in the causative factors occurred in 1953.

Further analysis of the Longport data is facilitated if it is assumed as an approximation that the secular trend is determined by the ground-water withdrawls [*Barksdale, Sundstrom*, and *Brunstein*, 1936, pp. 97–99]. The following modified form [*Jacob*, 1946, pp. 629–646] of the *Theis* [1935, pp. 519–524] nonequilibrium equation is then applicable:

$$s = \frac{114.6Q}{T}\left(-0.577216 - \log_e \frac{1.87r^2S}{T} + \log_e t\right) \quad (4)$$

where T is the coefficient of transmissibility expressed as the rate of flow of water, in gallons per day, through a vertical strip of aquifer, one foot wide and extending the full saturated height, under a hydraulic gradient of 100 pct at the prevailing temperature of the water, S is the coefficient of storage of the aquifer or the volume of water it releases from or takes into storage per unit surface area of the aquifer per unit change in the component of head normal to that surface, Q is the pumping rate, in gallons per minute, and r is the distance from the observation well to the center of pumping, in feet.

Comparing (4) with (1)

$$K_1 = \frac{114.6Q}{T}\left(-0.577216 - \log_e \frac{1.87r^2S}{T}\right)$$

and

$$K_2 = \frac{114.6Q}{T} \quad (5)$$

For (5) to be strictly applicable, Q must be a constant, whereas the pumping rate from the Atlantic City 800-foot sand varies with time. However, average values of K_1 and K_2 were derived from the solution of (2), and average pumping rates can be used to approximate Q. The average pumping rate during the period 1925–1952, inclusive, was 5800 gallons per minute. The average pumping rate in 1917–1925 was estimated from *Barksdale, Sundstrom*, and *Brunstein* [1936, p. 13] as 3750 gallons per minute. Therefore, Q, the pumping-rate change causing the drawdowns s, was taken as 2050 gallons per minute and was assumed to occur suddenly. The distance from the observation well to the center of pumping r was approximately 29,000 ft from a weighted average of the distances to the individual wells.

The solutions of (4) and (5) gave T = 50,000

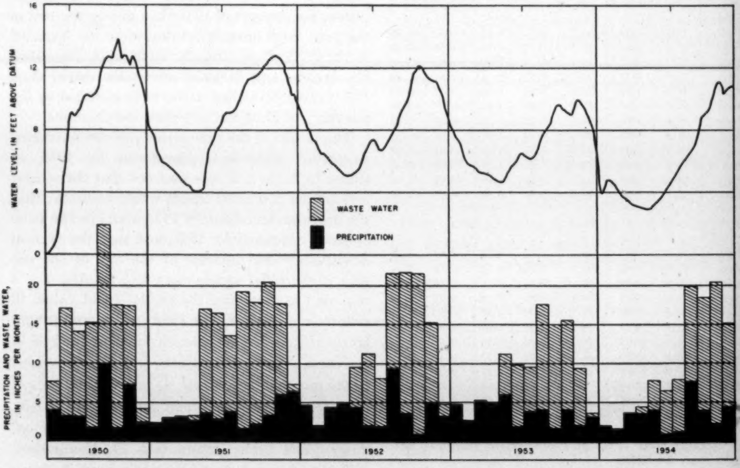

FIG. 2 – Composite hydrograph of wells in the Seabrook spreading area compared with precipitation and waste water

gallons per day per foot and $S = 0.0003$. This agrees with the results of a pumping test at Pleasantville, where T was about 60,000 gallons per day per foot and S was about 0.0003.

Analysis of water-level trends in the Seabrook spreading area—On a 390-acre woodland near Seabrook, N. J., 700 to 1200 million gallons of waste water are spread annually [*Remson*, 1954, pp. 4–15]. The infiltration capacity of the soil is large, and most of the applied water moves downward to the zone of saturation. The aquifer, thus recharged, is drained by streams along the margins of the area.

Figure 2 shows arithmetic averages of water-level altitudes above an assumed datum (average water-level of May 1, 1950) in 29 wells, precipitation, and amounts of applied waste water. Because the spreading pattern and water-level trends changed from year to year, the functional approach is preferable to the time-series approach for this analysis.

Consider a unit vertical prism of aquifer near one of the observation wells. The water balance for such a prism may be expressed as

$$q = w - S(\Delta h/\Delta t) \tag{6}$$

where $q =$ the difference between the rates of ground-water flow into and out of the unit prism
$w =$ the rate of recharge to the prism from above the water table
$S =$ the coefficent of storage of the aquifer
$\Delta h/\Delta t =$ the time rate of change in the altitude of the water table in the unit prism

Assume as approximations, that flow from the ground-water divide to the streams is linear and that S, w, and $\Delta h/\Delta t$ are constant along the entire flow line. Then, q is constant over the flow line, and

$$q_t = q(L - x) \tag{7}$$

where $q_t =$ the total average rate of ground-water discharge through the unit prism
$x =$ the distance from the external hydraulic control, the stream draining the spreading area, to the center of the unit prism
$L =$ the total distance from the stream to the ground-water divide

If the ground-water flow follows Darcy's law the total average discharge through the unit prism may be expressed as

$$q_t = T(dh/dx) \tag{8}$$

where $T =$ the coefficient of transmissibility
$dh/dx =$ the hydraulic gradient or the space rate of change of the altitude of the water table

If it is assumed as an approximation that T is a constant, (7) and (8) may be equated, rearranged, and integrated along the flow line between the stream and the unit prism.

$$\int_0^x (L - x)\, dx = (T/q) \int_H^h dh$$

$$q = \frac{T(h - H)}{Lx - x^2/2} \tag{9}$$

where $H =$ the altitude of the water level in the stream, coinciding with the water-table altitude at the stream position
$h =$ the altitude of the water table in the unit prism, at a distance x from the stream

If a more rigorous approach is required, the product of permeability and saturated thickness can be used instead of T.

From (6) and (9)

$$w = S(\Delta h/\Delta t) + \frac{T(h - H)}{Lx - x^2/2} \tag{10}$$

For a single observation well, x and L are constants. Two constants, A and B, therefore may be chosen so that

$$A = \frac{2T}{2Lx - x^2} \text{ and } B = AH \tag{11}$$

Then

$$w = S(\Delta h/\Delta t) + Ah - B \tag{12}$$

can be used as the functional equation to represent the hydrologic changes in the vicinity of any observation well. The time lags between the different factors in (12) could be neglected at Seabrook because of the large water applications and the use of monthly data.

The rate of recharge to the water table w may be evaluated from

$$w = p + b - g - e - \Delta v/\Delta t \tag{13}$$

where p = the rate of precipitation
b = the rate of waste-water spreading
g = the rate of direct runoff to the streams
e = the rate of evapotranspiration
$\Delta v/\Delta t$ = the rate of change of soil-moisture storage, positive for an increase in soil-moisture storage and negative for a decrease in soil-moisture storage

Much of the spreading area was constantly wet because of the water spreading. Therefore, evapotranspiration was evaluated by using the *Thornthwaite* [1948, pp. 54–94] formula for potential evapotranspiration.

Because of the large quantities of water entering the spreading area, the soil-moisture reservoir remained essentially full, and $\Delta v/\Delta t$ was zero for all practical purposes. Furthermore, there was no direct runoff because of the large infiltration capacity. Therefore, (13) becomes

$$w = p + b - e \tag{14}$$

When using (13) and (14), it is assumed that no ground-water is lost by evapotranspiration. Then, the rate of ground-water recharge per unit area w is always positive or zero.

Eq. (12) modified by (14) applies to a single unit vertical prism of the aquifer in the vicinity of one observation well. Assuming that the ground-water activity is adequately sampled by the observation-well network and that S and T are constants, the separate equations for the prisms and observation wells can be totaled to give summation forms. However, the work of computation can be greatly reduced by using average values of x, L, H, and $\Delta h/\Delta t$ in the equations as an approximation. This is equivalent to replacing the 29 observation wells by a single average well.

The normal forms of (12) are readily derived by again applying the principle of least squares. They are

$$\begin{aligned} \Sigma w &= -NB + S\,\Sigma \Delta h/\Delta t + A\Sigma h \\ \Sigma(w\Delta h/\Delta t) &= -B\,\Sigma \Delta h/\Delta t + S\Sigma\,(\Delta h/\Delta t)^2 \\ &\qquad + A\Sigma(h\Delta h/\Delta t) \\ \Sigma(wh) &= -B\Sigma h + S\Sigma(h\Delta h/\Delta t) + A\Sigma\,(h)^2 \end{aligned} \tag{15}$$

where N is the number of items in the set of data to which the equations are being applied. Solving (15) for the 55 months of record, the functional equation for the spreading area was found to be

$$w = 0.17(\Delta h/\Delta t) + 1.65\,h - 4.60 \tag{16}$$

or

$$\Delta h/\Delta t = 27.06 + 5.82\,w - 9.71\,h \tag{17}$$

The standard errors are 0.69 for B, 0.04 for S, and 0.25 for A.

The coefficient of correlation between w and h is 0.72. The coefficient of correlation between $\Delta h/\Delta t$ and h is -0.10, indicating poor correlation as was to be expected. Finally, the coefficient of correlation between w and $\Delta h/\Delta t$ is 0.56. This relatively low value resulted from the uneven distribution of the spreading water. When spreading occurred in the vicinity of the wells, the measured water levels rose more than when equal amounts of water were spread between them. Large water applications near the streams affected composite water levels less than similar applications near the center of the area. Therefore, the assumption that w was uniform over the spreading area was not strictly true, and some errors were introduced.

Eq. (12) and (14) were used to predict rates of change of the composite water level $\Delta h/\Delta t$ for December 1954. For this period, b was zero, p was 3.87 inches per month, e was 0.52 inch per month, and h was estimated as 7.83 ft on the basis of previous water levels. Therefore, w was found to be 3.35 inches per month, and $\Delta h/\Delta t$ was computed as -40.9 inches per month. The actual value of $\Delta h/\Delta t$ was -36.8 inches per month. This is satisfactory agreement considering the approximations used in the derivation of the functional equation.

Analysis of water-level trends in the Hulsart well—The Hulsart well is near Old Bridge, N. J. The infiltration capacity in this area is large, and there is no nearby artificial recharge or artificial discharge of ground water. Water levels are controlled by natural hydrologic factors: precipitation, evapotranspiration, and natural ground-water discharge.

Figure 3 shows water levels in the Hulsart well. No secular trend is apparent in this hydrograph. The annual (seasonal) trend reflects the seasonal nature of the evapotranspiration. In general, most summer rainfall is used to replace depleted soil moisture, and little ground-water recharge occurs. However, an exceptionally heavy rain can restore the soil-moisture storage even in midsummer, and also recharge the gound-water reservoir causing departures from the seasonal trend.

The Hulsart water-level record is not suitable for time-series analysis because of the absence of clearly defined trends. From the known hydrology,

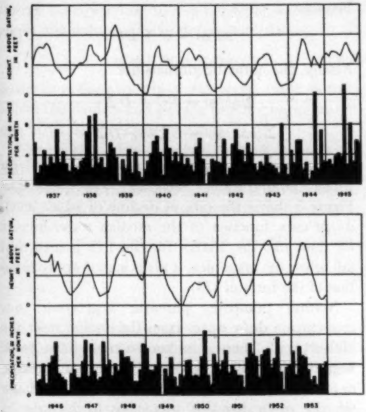

FIG. 3 – Hydrograph of the Hulsart well and precipitation

the functional type of approach is more applicable to this area.

Assume that flow from the ground-water divide to the stream is linear and follows Darcy's law. In addition, assume that S, $\Delta h/\Delta t$, w, and T are constant along the entire flow line through the Hulsart well. The functional equation (12), modified by (13), is then applicable. Because no data were used for times when the daily rainfall exceeded two inches, it can be assumed that the infiltration capacity of the sandy soil was never exceeded and that there was no direct runoff. Therefore, (13) becomes

$$w = p - e - \Delta v/\Delta t \tag{18}$$

Ground-water losses to phreatophytes and direct evaporation occur only in the vicinity of the stream, 500 ft from the Hulsart well. They do not affect the analysis because water lost in this area otherwise would have been discharged to the stream. Therefore, the evapotranspiration e in the vicinity of the Hulsart well is derived only from precipitation and soil moisture, and ground-water recharge w is positive or zero.

The distribution of rainfall and evapotranspiration within a given month is important in determining the amount of ground-water recharge, and monthly summations cannot be used for this computation. If soil moisture is to be taken into account, it is necessary to derive a daily or instantaneous water budget for the soil that involves w, p, and e. Because of the difficulty of this task, a different approach was used in analyzing the Hulsart records. This involved a separate analysis of data for periods of small change in soil-moisture storage and for periods of negligible ground-water recharge.

The average January evapotranspiration, based on the Thornthwaite equation, was 0.18 inch for the period of ground-water record. January precipitation averaged 3.87 inches for the same period. Therefore, practically every rainfall exceeded the soil-moisture deficiency and recharged the water table. Under such conditions, (18) can be evaluated on a monthly basis, $\Delta v/\Delta t$ being taken as zero. Thus, for the January data, (6) becomes

$$q = w - S(\Delta h/\Delta t) \tag{19}$$

where

$$w = p - e$$

Figure 4 shows the January relations between the water-level changes in the Hulsart well and precipitation minus evapotranspiration at the Runyon, N. J., weather station [U. S. Weather Bureau, 1937–1953]. The two points that fall above the main plot were disregarded because they reflect heavy rainfalls that took place at the ends of the preceding Decembers.

Ground-water discharge q depends upon the altitude of the water table h and tends to lower water levels. Because January is generally a time of rapidly rising levels, the relatively small tendency for ground-water discharge to lower the levels, and the effects of changing ground-water

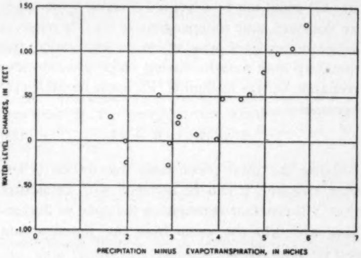

FIG. 4 – Relation between the January water-level changes in the Hulsart well and January precipitation minus evapotranspiration

discharge, are obscured. A plot of the rate of water-level change $\Delta h/\Delta t$ versus position of the water table h consequently showed no clear relationship between these two factors. Therefore, as an approximation, the ground-water discharge q was taken as a constant Q' for January regardless of the height of the water table, and (19) becomes

$$w = S(\Delta h/\Delta t) + Q' \tag{20}$$

For months during which there were only small water-level rises or there were declines, the effects of h and q did become significant. This explains the increased scattering of points in Figure 4 at low values of $\Delta h/\Delta t$. However, only negligible errors are likely to result from this scattering and the assumption of constant January ground-water discharge.

Eq. (20) and Figure 4 indicate a straight line with a slope equal to S and a w intercept equal to Q'. The normal equations for (20) are [*Arkin* and *Colton*, 1950, pp. 210–211]

$$\begin{aligned} \Sigma(w\Delta h/\Delta t) &= Q'\,\Sigma(\Delta h/\Delta t) + S\,\Sigma(\Delta h/\Delta t)^2 \\ \Sigma w &= NQ' + S(\Delta h/\Delta t) \end{aligned} \tag{21}$$

The solution of the normal equations gave a coefficient of storage S equal to 0.19 and a rate of ground-water discharge Q' equal to 3.04 inches per month for January. The standard error of estimate of w was 0.47, and the coefficient of correlation was 0.92. Therefore, the equation describing the January data can be written as

$$w = 0.19(\Delta h/\Delta t) + 3.04 \tag{22}$$

where

$$w = p - e$$

The computed rate of ground-water discharge in (22) could not be accepted because q was taken as constant and independent of h. Therefore, a separate analysis was made to determine this quantity from months during which ground-water recharge, w, was negligible. For such months, (12) becomes

$$S(\Delta h/\Delta t) = B - Ah \tag{23}$$

Because the total water-table fluctuation is less than five feet, it can be assumed with confidence that S is constant throughout the zone of fluctuation, and 0.19 the value from the January data can be used. Then

$$0.19(\Delta h/\Delta t) = B - Ah \tag{24}$$

Let $C = B/0.19$ and $D = -A/0.19$, and (24) becomes

$$\Delta h/\Delta t = C + Dh \tag{25}$$

Finally, the normal equations are

$$\begin{aligned} \Sigma\Delta h/\Delta t &= NC + D\,\Sigma h \\ \Sigma(h\Delta h/\Delta t) &= C\,\Sigma h + D\,\Sigma(h)^2 \end{aligned} \tag{26}$$

Data were examined, and months selected for which ground-water recharge was negligible. Figure 5 shows the rate of decline of water levels $\Delta h/\Delta t$ as a function of the median water-level h for these months. Except for the five points that fall below the main plot, it gives a good approximation of the form of (25).

Neither pumping, phreatic vegetation, nor evaporation draw water from the aquifer near the Hulsart well. There is no known cause for w to be negative, for ground-water declines to be excessive, or for individual points in Figure 5 to plot too high. On the other hand it was easy to include in Figure 5 months during which substantial recharge did occur. Such data would plot too low. Therefore, the five points in question probably represent months for which w was not negligible, and they were eliminated from the computations.

The solution of the normal equations for the 18 'fair-weather' months was found to be $C = -4.31$ and $D = -2.54$, or $B = -0.82$ and $A = 0.48$. From (24), the fair-weather equation for the Hulsart well is

$$0.19(\Delta h/\Delta t) = -0.82 - 0.48h \tag{27}$$

The standard error of estimate of $\Delta h/\Delta t$ is 0.72, and the coefficient of correlation is 0.84. Furthermore, from (9) and (11), the ground-water dis-

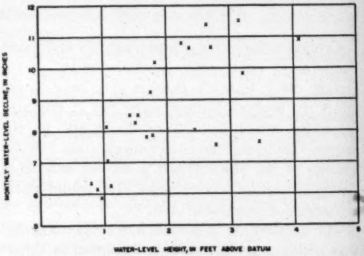

FIG. 5 – Relation between water-level decline and water-level height in the Hulsart well during months when rainfall did not exceed the soil-moisture deficiency

charge corresponding to any height of water table above the datum may be determined. It is

$$q = 0.82 + 0.48h \tag{28}$$

where h is the altitude of the water table in feet above the datum, and q is the rate of ground-water discharge in inches per month.

The result of the January analysis, $S = 0.19$, and the result of the fair weather analysis, $q = 0.82 + 0.48\ h$, may be substituted into (6) to give the full equation for the Hulsart well

$$w = 0.19\Delta h/\Delta t + 0.48h + 0.82 \tag{29}$$

where

$$w = p - e - \Delta v/\Delta t$$

and w cannot be negative, as explained above. Thus, although this expression could not be derived by simultaneous use of all available data, it was estimated from selected parts of the data.

Some important hydrologic quantities can be estimated from the well-trend equations if it is assumed that the Hulsart well is an accurate indicator of the ground-water activity in its area. For example, (29) could be used to estimate evapotranspiration for the Hulsart area if soil-moisture measurements were available. On the other hand, if values of e were available, it could be used to estimate changes in soil-moisture storage.

From (11), $H = B/A = -1.71$ ft below the datum for the Hulsart well. Because the altitude of the datum is 95.59 ft above mean sea level, the base level of flow is 93.88 ft above mean sea level. This figure is in accord with estimates of the altitude of the stream draining the area.

The distance x from the Hulsart well to the nearest stream is approximately 500 ft. The distance L from the stream to the divide is approximately 900 ft. Therefore, according to eq. (11), $T/A = 325{,}000\ \text{ft}^2$. According to the least-squares analysis, A is 0.48 per month. Therefore, T is approximately 40,000 gallons per day per foot in the vicinity of the Hulsart well. The permeability of the Englishtown sand, which underlies the Hulsart area, is highly variable [*Barksdale, Johnson, Baker, Schaefer*, and *DeBuchananne*, 1934, p. 41], and data are not available for an appraisal of this value.

Conclusions—Data from three hydrologically different areas were analysed in order to demonstrate the versatility and usefulness of statistical methods for the analysis of water-level trends. The results are approximate because of the assumptions that were made. However, the purpose of this paper is to demonstrate and encourage the use of these and similar techniques rather than to solve specific hydrologic problems. Furthermore, other hydrologic techniques can not always be used because of limited data. In such cases, these statistical analyses must be considered as preliminary attempts to estimate important hydrologic quantities.

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Use of Infiltration Equation Parameters to Evaluate Infiltration Differences in the Field

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Abstract—The infiltration equations $y = At^B$ and $dy/dt = a + b/y$ have appeared in the literature, where y is the quantity of water which will enter a soil when water is applied to the surface, and t is the time. In the present investigation, the constants A, B, a, and b, are considered for their usefulness in characterizing infiltration in field basins on Greenfield loamy sand, a deep soil without profile development. The product parameter AB is compared with a parameter R_T which is simply the average rate over the first two hours of infiltration. The results show AB to be 40 pct better statistically than R_T. On the other hand, $a + 10b$, which is superior to a alone and b alone, is essentially no better statistically than R_T.

INTRODUCTION

It is well known that the infiltration of water ponded on a soil surface proceeds at a rate which diminishes with time. In some cases a steady value is approached asymptotically, which value has significance in spreading recharge techniques. It does not necessarily have meaning for the irrigationist whose primary concern is with the early stages of the infiltration process. In these stages changes in the slope of the water-time curve are maximal, thus making it difficult to determine the infiltration status of a given soil.

A simple approach to the problem is to specify arbitrarily some constant time interval and express the infiltration status as the average rate of water absorption over the interval. Or, one can use the average rate over the time interval required to absorb a constant quantity of water, as has been done by *Huberty* and *Pillsbury* [1941], *Reitemeier* and *Christiansen* [1946], and *Burgy* and *Luthin* [1956]. Finally, if the infiltration process can be represented mathematically, one could use equation parameters to express the infiltration status. This is the objective of the present paper.

INFILTRATION EQUATIONS

Historical—For one-dimensional downward infiltration, with a film of ponded water, *Gardner* and *Widtsoe* [1921] gave an equation of the form

$$x = c_1t + c_2(1 - e^{-\beta t}) \tag{1}$$

where x is the depth to the wetted front, t is the time, e is the base of natural logarithms, and c_1, c_2, and β are constants. *Horton* [1939] proposed a rate equation which when integrated leads to the form

$$q = f_ct + (f_0 - f_c)(1 - e^{-kt})/k \tag{2}$$

where q is the quantity of water, f_c is the asymptotic steady rate, f_0 is the initial rate, and k is a constant. If the x of (1) is interpreted as the quantity of water q, then (1) and (2) become synonymous since one can set $\beta = k$, $c_1 = f_c$, and $c_2 = (f_0 - f_c)/k$. Eq. (2) attempts a more specific interpretation of constants by the introduction of f_0 and f_c, but is difficult to use since there are three constants to be evaluated experimentally.

A simpler two-parameter empirical equation has appeared in the literature. It is

$$y = At^B \tag{3}$$

where y, expressed as a depth of water, is the quantity of water infiltrated in time t, A is a constant, and B is a dimensionless positive exponent smaller than unity. The year 1926 marks an early attempt to use this equation even though it was not published until 11 years later [*Lewis*, 1937]. *Kostiakov* [1932] considered a functional relation which can be extended to yield (3). *Free*, *Browning*, and *Musgrave* [1940] found that (3) would satisfactorily fit the data for 68 soil profiles, but made no attempt to use its parameters as infiltration indices. However, *Tisdall* [1950] calculated values of A and B for several different soil conditions, and later [*Tisdall*, 1951] correlated both A and B with the level of the antecedent soil moisture.

Horton [1941] has criticized (3) because the differentiated form of the equation implies (i) an infinite initial rate, and (ii) an ultimate final rate of zero. The difficulty in (i) could be removed by adding small constants to y and t in (3), but for most cases of practical interest, these constants would be negligibly small. Hence, (3) suffices unless one is concerned specifically with the behavior of dy/dt for values of time very near zero.

In regard to (ii), no difficulty is encountered if one considers only early and intermediate stages of infiltration. *Tisdall* [1951] reports that (3) will hold up to 16 hours but that A and B can be determined in only a few hours.

Philip [1954] derived an infiltration equation using Darcy's law and several experimental generalizations. It is, with some change in symbols,

$$\frac{dy}{dt} = \frac{k_h}{\mu}\left[1 + \frac{(\bar{m} - m_0)(P + H)}{y}\right] \tag{4}$$

where y is the surface depth of water absorbed, k_h is the conductivity, μ is the viscosity of water, $\bar{m}$ and m_0 are the overall-average and initial moisture contents respectively (volume basis), P is the capillary head, and H is the height of water on the surface of the soil. Eq. (4) is attractive because it is derived theoretically, but investigation shows that the functional relationship which it specifies for y versus t is no different from that found by applying Poiseuille's law to a bundle of circular non-interconnected capillary tubes.

Adaptation and interpretation of equations—If a level field basin is filled with water of depth H_1, the amount of water absorbed with time can be determined by following the subsidence of the water surface with a hook gage. Time is required to fill the basin, and to allow calming of the water surface for the initial measurement. As subsequent measurements are taken, differences z between successive levels and the initial level represent the amount of water absorbed, not from time $t = 0$ but from $t = t_0$, where t_0 is the time of the initial measurement. Assuming that (3) holds from $t = 0$, but that the curve is established only by measurements at t_0 and at times thereafter, (3) becomes

$$z + y_0 = At^B, \tag{5}$$

where y_0 is the depth of water presumed to have been absorbed during the interval t_0. Now $y_0 = At_0^B$, and (5) becomes

$$z = At^B[1 - (t_0/t)^B] \tag{6}$$

The value of B is on the order of $\frac{1}{2}$; in the experimentation to be reported in this study it varied from 0.35 to 0.70. Setting $B = \frac{1}{2}$ in the brackets of (6), putting primes on the A and the remaining B, and dividing through by $(1 - \sqrt{t_0/t})$, leads to

$$z' = A't^{B'} \tag{7}$$

where

$$z' = z/(1 - \sqrt{t_0/t}) \tag{8}$$

Plotting (3) on log-log paper results in a straight line of intercept A and slope B. Eq. (7) will not yield theoretically straight lines when plotted similarly, but up to times t on the order of 1000 minutes, the curvature is negligibly slight. Hence, a log-log plot of (7) is essentially a straight line, but $A' \neq A$ nor does $B' = B$, unless $B = \frac{1}{2}$. By graphing (7) for various values of B and a constant t_0, a curve can be constructed which gives B as a function of B'; also a factor F can be obtained as a function of B', so that $A = A'F$. Thus, if t_0 is made the same for all experiments, and if simultaneous values of z and t are obtained, z' values can be calculated from (8) and a log-log plot of z' versus t will yield values of A' and B' of (7), which finally lead to the values of A and B.

Having shown how to obtain A and B for a field case it is desirable to show how they can be interpreted. It is reasonable to assume that both A and B will reflect soil and water conditions as they affect infiltration. Intuitively, then, it would seem that some combination of A and B might be a better index of infiltration than either A or B alone.

Referring to (3), the average infiltration rate over the time interval t is y/t. Thus,

$$\text{average rate} = y/t = At^{B-1}$$

At unit time, $t^{B-1} = 1^{B-1} = 1$; hence, A is numerically equal to the average rate over the first unit time interval.

If (3) is differentiated with respect to time t, the result is

$$\frac{dy}{dt} = ABt^{B-1} = \text{instantaneous rate}$$

From this it is seen that AB, a combination parameter, is numerically equal to the instantaneous rate at the end of the first unit time interval. If now the ratio of the instantaneous rate to the average rate is formed, the result is

$$\text{inst. rate/aver. rate} = B$$

and B is seen to be synonymous with the ratio of the instantaneous rate to the average rate, the instantaneous rate being measured at $t > 0$, and the average rate being measured over the total time interval t. Thus B is an expression of curvature, and its magnitude indicates how well the infiltration rate will hold up with time.

Another equation can be developed on the basis of (4). Assume that a depth of water H_0 is applied instantaneously to the soil surface in the basin at $t = 0$. Head H decreases with time and is equal to $H_0 - y$, where y is the height of water absorbed. Making this substitution and regrouping terms results in

$$dy/dt = a + b/y \tag{9}$$

where constants a and b are given by $a = k_h(1 - \bar{m} + m_0)/\mu$ and $b = k_h(\bar{m} - m_0)(P + H_0)/\mu$.

Again it is not possible to apply H_0 instantaneously. In practice, H_1 is applied within the interval t_0, during which time the depth y_0 has been absorbed. Hence, as in (5), $y = y_0 + z$, which gives

$$dz/dt = a + b/(y_0 + z) \tag{10}$$

In a plot of dz/dt versus $1/(y_0 + z)$, the slope of the straight line is b, with intercept a. The quantity y_0, made small by keeping t_0 small, is estimated by multiplying t_0 by the rate (estimated from the graph of z versus t) at $t = t_0$.

Parameter a, with dimensions of velocity, is the asymptotic final rate referred to in the introduction, while b, with dimensions of length × velocity, is a measure of the change in rate with depth of water absorbed. On the basis of *Philip's* [1954] derivation, a and b have the further interpretations (as functions of conductivity, moisture, viscosity, and head) given above in connection with (9).

A combination parameter using both a and b can be obtained by choosing some reasonable value of $y_0 + z$ in (10). In the present study this was arbitrarily chosen to be $y_0 + z = 0.1$ ft. Hence, the sum $a + b/0.1 = a + 10b$ is a combination parameter which can be interpreted as the instantaneous rate of water absorption when 0.1 ft of water has moved into the soil.

The quantities A, B, a, and b will contain, implicitly or explicitly, the effects of initial soil moisture, viscosity, and surface head. In any experimentation, these factors must be standardized so that they will not introduce extraneous variations in the infiltration indices.

Experimental Procedure

In May 1955, 32 level basins 10 by 15 ft were constructed on Greenfield loamy sand at the University of California Antelope Valley Field Station, Lancaster, California. Pre-treatment irrigations of four inches of water each were applied on July 12, 18, 25, and Aug. 11. On the last date, subsidence of the water level in each basin was recorded with time.

On Aug. 23, four surface amendments, consisting of ferrous sulfate (1 ton/acre), ferric sulfate (1 ton/acre), gypsum (5 tons per acre) and alfalfa straw (10 tons/acre) were applied at random to 24 basins (6 basins per amendment), leaving 8 basins as untreated checks. On Sep. 8, Sep. 22, Oct. 6, and Oct. 27, four inches of water was applied to each basin and subsidence of the water surface in each basin was recorded with time. Appreciable plant growth was not permitted; water loss from a basin between application dates was limited to evaporation, and seepage into deeper regions of soil. This procedure, along with the pre-treatment irrigations, was necessary to provide uniformity of soil moisture.

In obtaining rate measurements, water was directed into a basin at time $t = 0$, continuing until the water in the basin reached a height $H_1 = 4$ in. (same for all basins). Shortly after, at $t = t_0 = 5$ min, the initial reading of the water level was taken with the hook gage. Additional readings were taken at convenient subsequent times. A photograph of the experimental arrangement is shown in Figure 1.

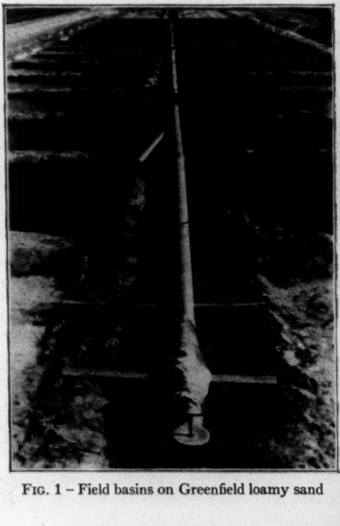

FIG. 1 – Field basins on Greenfield loamy sand

Values of A, B, a, and b were calculated as described in connection with (8) and (10). In addition, R_T, the average rate of water absorption over the first two hours, and R_w, the average rate of absorption during the time required to absorb 0.1 ft of water, were determined. R_T was calculated as the quotient of the value of z at $t - t_0 = 2$ hr divided by 2 hr. R_w was the quotient of 0.1 ft divided by the time (in hr), reckoned from t_0, required for 0.1 ft to be absorbed. Thus, eight parameters, or infiltration indices, A, B, AB, a, b, $a + 10b$, R_T, and R_w were determined for each basin and each date.

COMPUTATIONAL ANALYSIS

Statistical approach—Faced with an array of possible infiltration parameters, one must decide which parameter is best for the objective at hand. In the experimentation just described, the original objective was to assess the infiltration effects of the four amendments as compared to the untreated check. One would choose the parameter which is sensitive to changes in infiltration caused by the amendments, but which at the same time possesses a minimal variance for a given amendment or untreated check. Statistically this is equivalent to choosing the parameter which on the average yields the highest value of Student's t, since this statistical quantity depends upon both the difference between treatment means and the variance among the observations from which the mean is calculated.

For any parameter P (where P might be A, B, AB, a, b, $a + 10b$, R_T, or R_w) on Sep. 8 or later, the observations, or P-values, can be analyzed simply as a completely randomized experiment of five 'treatments' (four amendments plus check). The residual (or 'error') variance is estimated by a pooled overall estimate V, containing 27 degrees of freedom. Multiplying V by $(\frac{1}{6} + \frac{1}{8})$ and taking the square root yields $s_{(\bar{x}-\bar{x}_0)}$, the standard error of the difference between any treatment mean $\bar{x}$ and the check mean $\bar{x}_0$. Then t is calculated in the usual manner as the ratio of $\bar{x} - \bar{x}_0$ to $s_{(\bar{x}-\bar{x}_0)}$.

These amendment-versus-check comparisons do not admit of completely accurate probability statements since they involve non-orthogonal treatment comparisons [*Ostle*, 1954, p. 273]. The inaccuracy, however, is not nearly as extreme as in the calculation of a least significant difference (LSD) since not all possible comparisons are considered. The non-orthogonality could be avoided by calculating individual standard errors for each $\bar{x} - \bar{x}_0$, but this implicitly forces the assumption of a common overall residual variance, which variance should better be estimated by the pooled overall estimate than by individual estimates.

Comparison of parameters—For any single date an analysis of variance, along with the amendment mean differences, leads to four t-values for a parameter P. An analysis of variance for each date results in 16 t-values altogether. Sixteen t-values can similarly be calculated for any parameter P' different from P.

One simple procedure for deciding whether P is better (or poorer) than P' is to adopt a given probability level α and then to choose P rather than P' if P yields the larger number of t-values greater than t_α. A refinement in the procedure would be to vary α from say 1 to 5 to 10 pct and demand, if P is to be termed 'best', that it exhibit a trend of superiority throughout this range of α-values. All possible P versus P' comparisons would then show which parameter, if any, was superior to all of the others.

A more quantitative comparison can be obtained from an average based upon individual comparisons between the 16 corresponding t-values for P and P'. Defining $E(P$ versus $P')$ as an efficiency comparison between P's in which P' is the basis of comparison, $i(= 1, .., 4)$ as the summation index for the amendments, and $j(= 1, .., 4)$ as the summation index for the dates, the comparison is formulated as

$$E(P \text{ vs. } P') = \frac{1}{16}\sum_{j=1}^{4}\sum_{i=1}^{4}\left[\frac{200(t_{ij} - t'_{ij})}{t_{ij} + t'_{ij}}\right] \qquad (11)$$

where t_{ij} is the value of t for the ith amendment and jth date calculated on the basis of parameter P, and t'_{ij} is the similar value of t calculated on the basis of P'. The term in brackets is simply the percentage difference between t_{ij} and t'_{ij}, based upon the mean value of t_{ij} and t'_{ij}.

If $t_{ij} = t'_{ij}$, this is the condition of equivalence between P and P', and $E(P$ versus $P') = 0$. If $t_{ij} > t'_{ij}$ occurs more often and/or to greater degree than $t_{ij} < t'_{ij}$, $E(P$ vs. $P')$ will be a positive percentage and P is considered better than P'. If $t_{ij} < t'_{ij}$ occurs more often and/or to greater degree than $t_{ij} > t'_{ij}$, $E(P$ vs. $P')$ will be a negative percentage and P is considered poorer than P'. Respective maximal and minimal values of $E(P$ vs. $P')$ are $+200$ and -200 pct.

It follows from (11) that the form of the expression for $E(P'$ vs. $P)$, the inverse comparison, is the same as the right-hand side of (11) but with a negative sign. Hence, $E(P'\text{ vs. }P) = -E(P\text{ vs. }P')$, and the magnitude of the efficiency comparison is the same regardless of the order in which E is set up, whether P vs. P', or P' vs. P.

Before the formulation of (11) was decided upon, attempts were made to develop an efficiency comparison involving the ratio t_{ij}/t'_{ij}, but difficulties were encountered. The magnitude of the comparison was not independent of the order of the comparison, nor was the sign always correctly related to the order.

The $E(P\text{ vs. }P')$ of (11) can be further modified to provide an efficiency comparison on the basis of t-values greater than t_α as mentioned earlier. This is done by eliminating from the summation in (11) each (t_{ij}, t'_{ij}) pair in which neither t_{ij} nor t'_{ij} is equal to or greater than t_α. For each (t_{ij}, t'_{ij}) pair eliminated, the 16 in (11) must be diminished by 1. If the modified $E(P\text{ vs. }P')$ remains positive as α varies through a range of values, the trend thus established more than ever indicates P as superior to P'.

TABLE 1 - *Expression of parameter R_T according to methods I, II, and III*

Date	Basin 3[a]			Basin 9[a]			Basin 16[a]		
	Method			Method			Method		
	I	II	III	I	II	III	I	II	III
	10^{-3} ft/hr	10^{-3} ft/hr	pct	10^{-3} ft/hr	10^{-3} ft/hr	pct	10^{-3} ft/hr	10^{-3} ft/hr	pct
Aug. 11.	83	—	—	46	—	—	64	—	—
Sep. 8 . .	72	−11	87	71	+25	154	49	−15	77
Sep. 22 .	62	−21	75	59	+13	128	37	−27	58
Oct. 6 . .	51	−32	61	46	0	100	27	−37	42
Oct. 27 .	55	−28	66	42	−4	91	34	−30	53

[a] On Aug. 23, Basin 9 was treated with alfalfa straw, and Basin 16 with ferrous sulfate, while Basin 3 remained as an untreated check.

Reference data—The pre-treatment data of Aug. 11, hereinafter referred to as the reference data, represent the infiltration status prior to application of the amendments. As has been done by *Huberty* and *Pillsbury* [1941], it appears desirable to utilize the pre-treatment information to reduce variability within treatments. Perhaps the simplest method is to express the basin parameters for Sep. 8 and later as differences from the corresponding reference (Aug. 11) parameters, and then to calculate the analysis of variance and the resulting t-values on the basis of these differences. Designating this procedure as Method II, and the previous analysis of variance (not using the reference data) as Method I, one can for each parameter compare Methods I and II, both on the basis of number of t's greater than t_α, and by the use of an $E(M\text{ vs. }M')$ defined as equal to the right-hand side of (11), where M refers to one method and M' to another, the difference between t_{ij} and t'_{ij} being due to method.

Since overall proportional effects of temperature dependent viscosity and soil moisture can appear from date to date, another reasonable procedure, call it Method III, consists of an analysis of variance of the ratios, expressed as percentages, of the basin parameters on Sep. 8 and later to the corresponding basin parameters on Aug. 11. Comparison of Method III with I and II can be as described in the preceding paragraph.

Finally, one could try a covariance analysis in which the reference parameters (Aug. 11) are treated as the concomitant variable. However, a

TABLE 2 - *R_T data, method I, and analysis of variance for Sep. 8*

	Treatment				
	Check[a]	Ferrous[a]	Ferric[a]	Gypsum[a]	Alfalfa[a]
	60	55	68	61	71[b]
	72[b]	42	54	59	83
	49	49[b]	40	59	102
	60	55	56	46	110
	85	41	34	86	63
	48	36	36	38	135
	35	. . .	. . .	. . .	. . .
	30	. . .	. . .	. . .	. . .
Total	439	278	288	349	564
Mean	54.9	46.3	48.0	58.2	94.0

Analysis of variance			
S. of V.	D. F.	S. S.	M. S.
Treatments . .	4	. . .	. . .
Error	27	8515.1	315.4
Total	31	. . .	. . .

$$s_{(\bar{x}-\bar{x}_0)} = \sqrt{315.4(1/6 + 1/8)} = 9.59$$

$$t_{\text{ferrous}} = (54.9 - 46.3)/9.59 = 0.896$$

[a] Values in 10^{-3} ft/hr.

[b] Sep. 8 values used for illustration in Table 1.

TABLE 3 – *Calculation of efficiency comparison, Eq. (11), for parameters AB and B, Method III*

Date and treatment	t-values		Eq. (11) bracket (AB vs. B)
	B	AB	
Sep. 8			
Ferrous	0.72	3.87	+137.2[a]
Ferric	1.25	2.36	+61.4[a]
Gypsum	0.76	1.09	+35.6
Alfalfa	3.93	27.23	+149.6[a]
Sep. 22			
Ferrous	0.22	1.18	+137.2
Ferric	1.09	0.18	−143.2
Gypsum	0.81	0.30	−91.8
Alfalfa	3.28	12.92	+119.0[a]
Oct. 6			
Ferrous	1.25	0.52	−82.4
Ferric	1.34	0.40	−108.0
Gypsum	2.86	1.15	−85.2[a]
Alfalfa	4.20	5.73	+30.8[a]
Oct. 27			
Ferrous	0.82	1.20	+37.6
Ferric	1.41	0.60	−80.6
Gypsum	2.45	2.07	−16.8[a]
Alfalfa	2.52	6.03	+82.0[a]
Mean			+11.4

[a] At least one *t*-value of the pair is greater than $t_{0.05}$ (= 2.05).

complete covariance analysis had to be abandoned after preliminary calculations showed that the regression coefficients inherent to the analysis could not be considered homogeneous.

Numerical illustration—Table 1 sets forth for three different basins the expression of R_T for Methods I, II, and III. The columns headed I contain simply the values of R_T on the various dates. Columns headed II contain R_T as differences from the reference R_T of Aug. 11. Columns headed III contain R_T as a percentage of the reference R_T.

Table 2 contains a complete set of data for R_T, Sep. 8, along with the analysis of variance table and the calculation of a single *t*-value. The calculation of the remaining three *t*-values is not shown. The basic procedure represented in Table 2 was carried through for each parameter, date, and method.

Table 3 sets forth the calculations represented by (11). Each entry in the fourth column is the bracket quantity of (11). Note that $P = AB$ and $P' = B$. From the bottom line of the table the mean value +11.4 indicates AB as superior to B. It can be seen from the fourth column and (11) that $E(B \text{ vs. } AB)$ is −11.4 pct instead of +11.4, showing that the sign of the percentage reflects the order of comparison.

The fourth column also illustrates the modification of $E(AB \text{ vs. } B)$ in accordance with the number of *t*-values greater than or equal to t_α, where $\alpha = 5$ pct. The modified $E(AB \text{ vs. } B)$ is the mean of the eight foot-noted values, rather than the mean of all 16 values, and is equal to the algebraic sum of the foot-noted values divided by 8, or +59.8 pct. When all 16 values are used, the α can be considered as 100 pct.

RESULTS

Validity of equations—If an equation parameter is to be used justifiably as an index of infiltration, it must be demonstrated that the equation itself can be used to represent the infiltration process. The type of agreement obtained for (7) is shown by the representative log-log plots of Figure 2. Of the total number of curves determined, 25 pct exhibited the near-perfect linearity of curve 1 of the figure, and 55 pct showed approximately the linearity of curve 2. Only 20 pct tended to show as much curvature as curve 3. Hence, the success of (7) in fitting these field data is deemed adequate.

The results of fitting the data according to (10) are shown by three representative curves in Figure 3. Thirty-six pct of the curves exhibited the near-perfect linearity of curve 1, while 25 pct exhibited far-end deviation of points similar

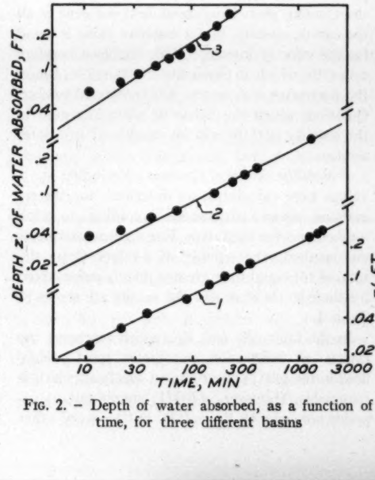

FIG. 2. – Depth of water absorbed, as a function of time, for three different basins

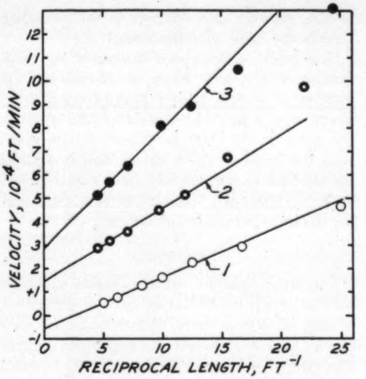

FIG. 3 – Velocity of water absorption, as a function of reciprocal depth absorbed, for three different basins

to curve 2, and 39 pct exhibited far-end deviations similar to curve 3. These deviations, which occur for small values of z [hence large $1/(y_0 + z)$], can be caused by uncertainties in the determination of y_0. The uncertainty becomes negligible as z becomes large enough to dominate $y_0 + z$. Practically without exception the linearity of all curves became almost perfect for the smaller values of $1/(y_0 + z)$.

Even though curve 1 (Fig. 3) shows near-perfect linearity, it illustrates a fundamental shortcoming present in about four per cent of all the curves; namely, that a negative value is found for the velocity intercept. This implies a negative a in (10), which is physically inadmissible; hence, the parameter a alone was not considered further. Questions which this behavior raises in regard to the validity of (10) will be considered in a later section.

Probability levels of t-values—Excluding a, t-values were calculated, as described, for the remaining seven parameters according to each method and for each date. For a given parameter and method, the number of t-values (from the total of 16) equal to or greater than t_α was counted for three levels of α, and the results are shown in Table 4.

In the table, R_T and R_w, which represent the classes of infiltration parameter most widely used in the past, appear almost identical, which is reasonable. However, AB(III) stands out as superior not only to R_T and R_w but to every other parameter and method in the table. The poorest parameter is b, while $a + 10b$ is essentially the same as R_T and R_w. With regard to methods, the order of goodness appears to be III > II > I. For Method I, in which the reference data of Aug. 11 are not used, B appears to be the best parameter. Finally, it also appears that the use of equation (3) is more fruitful than is the use of (9).

Efficiency comparisons—To provide a more quantitative comparison of the parameters against a prevailing type parameter, R_T(III) was chosen as P' in (11) and the other parameters were compared against it. The α-level was varied from 100 pct (or all 16 pairs of t) to 1 pct, and the results plotted as Figure 4A. The logarithmic scale is used simply to emphasize the smaller values of α, which are generally of most interest. Again it is noted that AB is outstanding, while $a + 10b$ is but slightly superior to R_T. Over the whole α-range, B and R_w must be taken as approximately equivalent to R_T, since for large α they are above R_T, and are below it for small α. A, and b especially, are decidedly inferior.

Also illustrated in Figure 4A is the effect of method, as shown by the three different point symbols. Preliminary calculations using (11) for a single parameter but varying methods (see *Reference data*, above) showed R_T(III) to be

TABLE 4 – *Number of t-values equal to or greater than t_α, for each parameter and method*

Parameter	Method	Number of t's $\geqq t_\alpha$		
		α = 10 pct	α = 5 pct	α = 1 pct
A	I	3	2	2
	II	4	4	2
	III	4	4	3
B	I	5	5	4
	II	6	6	4
	III	6	6	4
AB	I	3	3	2
	II	5	5	4
	III	7	7	5
b	I	2	2	1
	II	3	2	2
	III	3	3	2
$a + 10b$	I	3	3	3
	II	5	5	3
	III	5	5	5
R_T	I	3	3	3
	II	5	5	4
	III	5	5	5
R_w	I	3	3	3
	II	6	4	4
	III	5	5	4

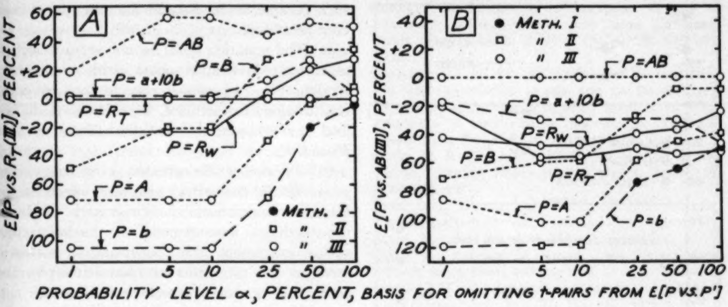

FIG. 4 – Efficiency comparisons for varying levels of probability, basis of R_T(III) and AB(III)

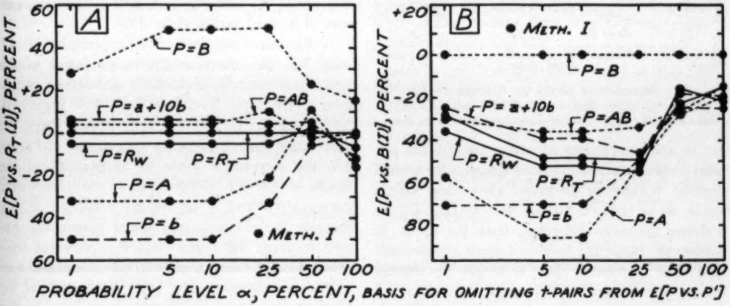

FIG. 5 – Efficiency comparisons for varying levels of probability, basis of R_T(I) and B(I)

superior to R_T(II) and R_T(I). Hence, with R_T(III) as P' in all cases, the efficiency comparison was calculated for each parameter according to each method. Each point used to represent the parameter in Figure 4A was that of the method, I, II, or III, which gave the highest value of the efficiency comparison percentage. It is obvious from the figure that in only a few cases (two) was Method I superior to the others, while for a few more cases (ten) Method II was superior, but in the majority of cases (thirty) Method III was superior. Extensive calculations, not reported here, in which comparisons of II versus I and III versus II were made on the basis of (11), showed conclusively that the order was III better than II better than I, which is in agreement with Table 4 and Figure 4.

Since Figure 4A contains R_T(III) as the basis of comparison, the only strictly accurate comparison involving AB is AB versus R_T. To see whether AB(III) is better than every other parameter and method, it must be made the basis of the comparison [P' in (11)]. Figure 4B, which is similar to Figure 4A except that AB(III) is the basis of the comparison, indeed shows that AB(III) is superior to all other parameters and methods.

The question now arises as to which parameter would be best if reference data were not available; that is, if I were the only possible method. This is shown in Figure 5, in a manner similar to Figure 4. In Figure 5A, the basis of comparison is again R_T, but since B appears best, it is made the basis of comparison in Figure 5B where its superiority is thus established. With the exception of the positions of AB and B, Figure 5 represents essentially the same picture as Figure 4.

Treatment effects—Although treatment effects

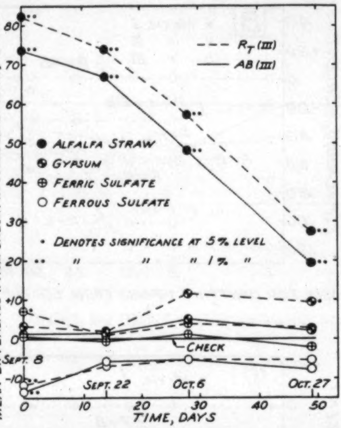

Fig. 6 – Amendment effects as differences from the check, as expressed by R_T(III) and AB(III)

per se and the reasons for them are not the primary considerations of this paper, it is still deemed worthwhile to show what these effects are in terms of both AB(III) and R_T(III). Figure 6 shows the mean difference, from the check, in parameter ratio for each amendment on each date. The 'parameter ratio' is simply the expression of the treatment effect when the reference data are utilized by the ratios of Method III, as illustrated in Table 1.

It is noted from Figure 6 that AB in general produces greater absolute differences than does R_T, as well as an increase from 5 to 7 of results significant at the 5 pct level (see also Table 4). It should be remembered that Figure 6 shows only mean differences, and does not include for AB(III) the additional effect of a lowered 'within' variance, which is included in the efficiency comparisons based on t and shown in Figure 4.

Concluding Remarks

On the basis of the results of this investigation, it can be stated:

(a) The equation $y = At^B$ serves very well to describe short-term infiltration into field basins.

(b) The parameter AB, which can be interpreted numerically as the instantaneous infiltration rate at unit time, is superior statistically to such parameters as R_T and R_w which have been used heretofore.

(c) The equation $dy/dt = a + b/y$, though it represents infiltration data with sufficiently straight lines, possesses one serious physical shortcoming; furthermore, its parameters do not lead to any appreciable statistical advantage over R_T and R_w.

(d) To realize the greatest gain from using $y = At^B$ in evaluating treatment effects of infiltration amendments, it is necessary to obtain pre-treatment measurements of the infiltration status, expressing each post-treatment measurement as the ratio of that measurement to the corresponding pre-treatment measurement.

(e) If pre-treatment measurements cannot be obtained, the use of $y = At^B$ is still better than the use of R_T and R_w, but in this event parameter B is used rather than AB.

A numerical estimate of the superiority of AB over R_T, (b) above, might be expressed as the percentage increase in number of t-values significant at the 5 pct level (see Table 4 or Figure 6). This would be $(7 - 5)100/5$, or 40 pct. From the more quantitative efficiency comparison of Figure 4A, the increase is given as 57 pct. Thus, the figure of 40 pct would seem to be sufficiently conservative and is tentatively accepted as the increase in efficiency one might reasonably expect in using AB rather than R_T, provided that pre-treatment measurements are available.

The advantage of the ratio method (that is, Method III) listed in (d) above is probably the result of two overall proportional effects: viscosity and moisture content. Flow of water is inversely proportional to the viscosity which in turn is temperature dependent. Temperature changes over the period from Aug. 11 to Oct. 27 would thus induce proportional effects into the flow parameters. Furthermore, on the basis of *Neal's* [1938] experiments, one can reason that progressive changes in the overall moisture content over the same time period could also, at least to a first approximation, induce proportional effects in the flow parameters. The ratio method removes these elements of variability.

The failure of the equation $dy/dt = a + b/y$ to yield parameters of appreciable statistical superiority, along with a tendency to predict physically inadmissible negative values of a, argues against using this equation for the specification of infiltration characteristics. However, it must be remembered that the theoretical derivation of (4) assumes all flow to be vertically downward. For the basins studied here (10 by 15 ft), the relative amount of lateral flow probably comes much closer to being negligible than it does for a small ring infiltrometer less than one square foot in cross section. However, this still does not quarantee that lateral movement for the basins was negligible; hence, the shortcomings of the equation may have been due to such lateral movement. To clear up this point, further investigation is needed.

Because of the success of the equation $y = At^B$, both physically and statistically, it would appear that future investigations involving infiltration might well be improved by the use of this equation and its parameters for specifying the short-term infiltration status of a soil.

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Problems Encountered in the Utilization of Ground-Water Reservoirs

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Abstract—Ground-water reservoirs are compared to surface-water reservoirs and the similarities and differences are pinpointed. For example, the boundaries and storage capacity of a water-bearing formation are not readily determinable. By comparison, an aerial survey of a potential reservoir site, from which a contour map may be prepared, is generally sufficient to determine the boundaries and storage capacity of any desired impoundment. Further, ground-water reservoirs are full to start with, whereas the area of an impoundment is usually devoid of water, except for a small amount contained in the river channel. Such differences, and others discussed in the body of the paper, give rise to social and engineering problems which are not duplicated elsewhere in the field of water-resource development. It may not be an exaggeration to state that, at our present level of technique and knowledge, the scientific and engineering problems are less vexing than the problems which must be solved by negotiation and persuasion. Examples of problems encountered in the utilization of ground-water reservoirs are cited. As case histories, problems of industrial ground-water supply in the East St. Louis area, and of municipal ground-water supply in the Canton, Ohio, area are discussed.

Definition of a reservoir—All functional reservoirs, surface and sub-surface, have certain characteristics in common. Any functional reservoir must admit water, store water, and permit water to be withdrawn economically. If an aquifer does not admit water but contains water and permits it to be withdrawn, it is not a functional reservoir, it is a mine. If it admits water and releases water, but does not store water, it is not a functional reservoir, it is a channel.

The differences between surface and sub-surface reservoirs are, of course, the source of the special problems connected with the utilization of aquifers. A point-by-point comparison is illuminating.

Reservoir capacity—The boundaries of a surface reservoir and its capacity are readily and rapidly determinable. Aerial photos combined with radar profiles and stereoscopic plotting, requiring only a minimum of ground control, will generally enable preparation of a contour map which can be used as the basis for selecting and evaluating dam sites in terms of potential impoundments.

Not so water-bearing formations. Not only is it a time-consuming, expensive task to delineate the boundaries of an aquifer, but the water-bearing materials are likely to be heterogenous, contain lenses of clay or silt, and be of different permeability in different places. Moreover, the storage coefficient of an aquifer can assume different values in different places and may change significantly, possibly by three orders of magnitude, as the aquifer is progressively dewatered or filled.

In addition to mapping, much test drilling, aquifer-performance testing, and hydrogeologic interpretation is required to determine the storage capacity of an aquifer. The work is complex, relatively expensive, and time-consuming. Moreover, the results of the work have a greater uncertainty factor than the analogous study of a potential surface impoundment.

Reservoir condition—A surface reservoir site is generally devoid of ponded water before an impoundment is created. A ground-water reservoir is usually full of water initially. This has certain social implications which will be touched upon later, and creates a series of problems of engineering negotiation that are not encountered elsewhere.

The quality of reservoir water—The approximate quality of water to be expected in a surface impoundment can be predicted in advance of construction by taking and analyzing samples from the water source over a period of years.

Not so a water-bearing formation. Samples of water from an aquifer may be satisfactory, but mineralized water may overlie or underlie the aquifer and the exact quality of water to be obtained may change with the rate and distribution of the offtake. In certain instances even after the most exhaustive studies the future quality of water may be more or less indeterminate. Evaluation of the quality of water to be expected from an aquifer is a matter of judgment, after the facts have been collected, assembled, and analyzed.

The filling and emptying of reservoirs—The usual surface impoundment is filled rapidly and at the maximum possible rate by the unrestricted flow of water in the river which has been dammed. It is discharged at any desired rate by opening a gate or valve, as required. There is little or no 'feed-back' effect. The rate of replenishment is not limited when the reservoir is not full.

Not so a sub-surface reservoir. Sub-surface reservoirs are replenished by water infiltrating from a surface source either by percolation from precipitation or by infiltration of water from a river which intersects the recharge area. Excluding limestone or basalt aquifers, which are recharged through sink-holes or fissures, the limit to the rate of recharge depends on the permeability of the outcropping materials and, probably equally important, on the hydraulic gradients created by the distribution of pumpage within the aquifer; that is, the rates and positions of the offtakes. Recharge is, therefore, dependent upon a factor that cannot be exactly evaluated before the aquifer is developed. This feed-back effect is a major factor in determining the rate of recharge.

Note that the bottleneck in recharge is matched by a bottleneck in offtake. Taking water from the ground-water reservoir is not a simple matter of opening a gate. The process involves construction of wells, and installation of pumps and power source. Even then, the amount available at any point of offtake is limited, in a complex manner, by the hydrogeological characteristics of the formation, the design of the well, and the pumpage from nearby wells.

The availability of recharge—In a surface impoundment, water entering one part of the reservoir immediately raises the level of water throughout the reservoir and thus makes all of the stored water more readily available for use.

Not so a sub-surface reservoir. Due to the slow movement of water through porous media, a reservoir may be replenished in one area and remain unreplenished in most of the area that it underlies. Thus the mere fact of recharge does not of itself assure us that a proportionate supply of ground water will be available throughout the aquifer. This important characteristic of aquifers is often overlooked in practice.

Negotiating problems—Even this brief summary may be sufficient to indicate the physical and technical differences between ground-water reservoirs and surface impoundments. A short discussion of the social problems and negotiating difficulties is now in order.

A surface reservoir lends itself to centralized control: land acquisition must occur in a large block, construction is large-scale, and operation is visible and readily controlled with a minimum of effort. Visible benefits such as flood control, irrigation, hydropower, water supply, and recreation may result from a single impoundment (although the operational requirements of each of these functions are not always compatible, especially as the size of impoundment increases and with it the possibility of year-to-year carry-over of stored water).

Utilization of aquifers has been more haphazard and the result of the initiative of individuals rather than governmental or collective effort. The replenishment of the aquifer, everybody's business, is nobody's business, until water levels drop. Aquifers contain a maximum quantity of water at the start of development and, because the amount in storage is so much greater than any possible surface impoundment, the supply is usually regarded as unlimited. It has generally happened that by the time collective action becomes necessary, a complex tangle of economic and legal relationships has been created and there are vested interests which operate on mistaken hydrogeologic assumptions.

Moreover, the technical problems of different aquifers are not identical. Unhappily, experience in negotiating a solution in one place is only generally helpful in solving problems in another place. For instance, the organization of a 'district' for artificial recharge to replenish an irrigation supply will differ considerably from that of a recharge 'district' organized to prevent intrusion of mineralized water to a fresh-water aquifer. It may be anticipated that a wide variety of administrative organizations, private and public, will be needed to cope with the many aspects of problems involved in the utilization of ground-water reservoirs, in contrast to the relatively few forms of the surface-water control district. Thus, skill at negotiation, and a broad, open-minded approach to the problem of utilization of aquifers, is essential. Even the most junior members of a technical organization must exercise tact and discretion lest, by some ill-considered statement, adverse public opinion be developed which will impede the purely technical program of study while, at the same time, hastening the organization of opposition to the subsequent recommendations.

Reasons for developing ground-water reservoirs—In reviewing the many complex problems in the field of ground water, problems which are difficult and expensive to solve, one may ask why development is justified at all. And this is probably the most important single question that must be answered. In the United States there is at least one hundred times as much water contained in aquifers as in all of our existing man-made impoundments. Since these water-bearing formations are approximately full to start with, the water can be obtained cheaply by individuals. This water is especially attractive during the first two or three decades of development since it is more reliable and can be brought into operation more rapidly than any comparable river source. When the water-bearing formations have been depleted, the potential reservoir capacity usually remains. It is of utmost importance to a nation that this reservoir capacity be utilized. Aquifers must be transformed from mines to reservoirs; the cost of study is minor compared to the cost of obtaining the same volume of storage in some other way.

Considered as storage reservoirs, aquifers are not subject to evaporation losses, they are not progressively reduced in capacity by deposition of sediment, no land is removed from cultivation, and last, but unfortunately of increasing importance, water in aquifers composed of granular materials is almost completely protected from radioactive fallout.

The problems of the continuing use of ground water are not problems of vast reclamation projects, which assume *a priori* the economic value of the results to be obtained by impounding vast volumes of water, and which are justified by postulated cost-benefits ratios. On the contrary, the substantial investments already in existence justify the costs of transforming ground-water mines into ground-water reservoirs. And although the cost of studies may seem high compared to the cost of analogous studies for storage of water upon the land surface, the cost of the projects is low compared to the cost of the same size water-storage development on the land surface.

The principal technical problem in the field of ground water is to devise a method for economically changing ground-water mines into reservoirs. The principal negotiating problem is to obtain the needed legal rules so that the technicians may do the most effective job in applying the techniques. At this time (1957), in my opinion, both problems await satisfactory solution.

Case histories—(1) The American Bottoms area, the flood plain of the Mississippi River opposite St. Louis, is a genuine ground-water reservoir. The sediments, mostly sand and gravel which were deposited in the bedrock channel of the Mississippi River some 20 to 30 thousand years ago, are permeable. Water withdrawn from wells is replaced by infiltration of water from the Mississippi River and by percolation of precipitation from the land surface. Total quantity of water in storage is about a million acre feet, comparable to the projected storage at Folsom Reservoir or Pine Flat Reservoir. It is one of the Nation's smaller ground-water reservoirs.

Annual ground-water offtake, replenished without special man-exerted effort, is estimated at about 15,000 acre feet a year. Computations show that by means of proper organization and construction, the total perennial supply could be raised to about 75,000 acre feet a year without artificial recharge, merely by positioning well fields in such a manner as to increase the natural recharge.

Single horizontal collectors, built on the river bank are operating at offtake rates of more than 10,000 gpm each. These are large, expensive units and their potential yields must be accurately determined in advance of construction. This is accomplished on the basis of the results of aquifer-performance tests, which give the effective transmissibility and effective distance to the 'line of recharge,' which data combined with information on stages of the river and water temperature, is the basis for computation.

The stage of the Mississippi River at St. Louis has been recorded daily since 1861, so the mean annual stage can be readily determined from a gage-height duration curve. The mean daily and monthly discharges are also a matter of record. We can also determine the frequency of any selected stage that has occurred and thus design conservatively. What, then, is the problem?

In the interest of navigation, the channel has been straightened and deepened. In the interest of flood control, levees have been built to constrict the flood flows. Thus at low rates of river flow the gage height is being progressively reduced because of channel improvements, whereas at flood discharges the gage height is being increased. This tends to distort and lower the position of the gage-height duration curve. Instead of the recorded mean river stage, elevation 390, we compute a mean river stage under present conditions of channel of, possibly, 387. Moreover, there is no assurance that, in the life of our installations this mean stage may not go down to 385. The situation makes for difficulty in computation and, because of reduction in head of the recharge water, for decreasing ground-water yields. But by judicious extrapolation of trends, decisions can be made; after all the mean annual discharge from a 700,000 sq mi drainage area is not likely to be changed. Nor will the mere redistribution of flood flows, by means of flood-control reservoirs such as those at

Garrison, North Dakota, and Oahe and Ft. Randall, South Dakota, and Fort Peck in Montana significantly change the mean annual discharge. Total usable storage when these and other reservoirs are completed will be about 60 million acre feet. By way of comparison the average annual discharge of the entire Mississippi-Missouri River System at St. Louis for the decade starting in 1940 was about 130 million acre feet.

Now, if the nature of the upstream developments were purely a matter of flood control it would not be very difficult to make an operational analysis of the system, including the effects of the flood-control reservoirs, and compute a useful, synthetic gage-height duration curve for, say, a 30-year period of record, using the observed discharges and modifying them in predetermined manner by the release of flood waters. This synthetic gage-height duration curve would enable us to determine probable future river levels and would substitute admirably for the now-valueless hydrographs of the river.

But, no. The storage of flood waters in the upper Missouri Basin has given rise to irrigation projects. The future consumptive use of water in the Missouri Basin for irrigation is now estimated at an average of 10 million acre feet a year. Naturally, during a dry period, this figure will rise and during wet years it may decline. Thus our operational analysis becomes exceedingly complex and, certainly, the average yearly discharge of the Mississippi at St. Louis will be at least seven per cent smaller due to consumptive use of irrigation water. In some years, like 1940, the annual flow might be reduced by 15 pct and the flow in a given month even more. It is virtually impossible to predict the occurrence and duration of low water periods and, for a ground-water supply replenished by river infiltration, these are crucial. There is no answer yet to this problem and no immediate answer should be expected, the hydraulic system is not in a state of steady-flow and the feedback effect is very large. The design of important ground-water facilities has become increasingly difficult due to the lack of assurance as to the probable reproducibility of past hydrologic events.

(2) A ground-water reservoir problem that was solved in a satisfactory manner is located near Canton, Ohio. In 1946, following general studies by the Ohio Water Resources Board and the Ground Water Branch of the U. S. Geological Survey, the City decided to have detailed engineering studies made in an area it owned in the northwest section of town (Fig. 1). There is a buried valley running in a southwesterly direction. On the land surface a small stream, West Branch of Nimishillen Creek, intersects the ancient buried valley. Exploration and aquifer-performance tests showed that there were two aquifers in the area, separated horizontally by a tough, impermeable clay which was probably deposited during a long period of ponding after the first retreat of the glaciers. Figure 2 shows the two piezometric surfaces and their relationship to the buried valley. The aquifers are demonstrably separate.

This was the situation: the upper aquifer was in

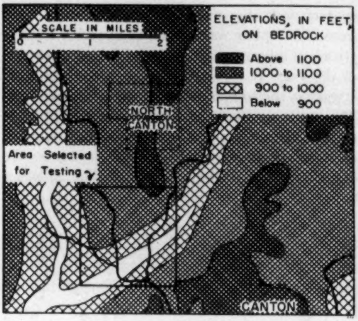

SCALE IN MILES
0
1
2
ELEVATIONS, IN FEET, ON BEDROCK
Above 1100
1000 to 1100
900 to 1000
Below 900
NORTH CANTON
Area Selected for Testing
CANTON

FIG. 1 – Map of bedrock surface, showing location of area studied

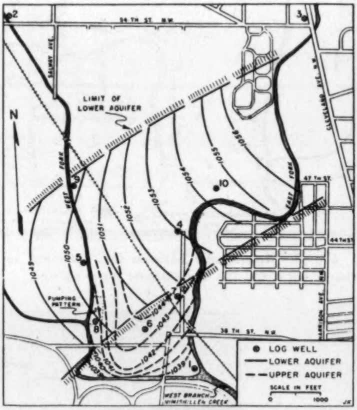

34TH ST. N.W.
SALWAY AVE.
CLEVELAND AVE. N.W.
LIMIT OF LOWER AQUIFER
N
WEST FORK
EAST FORK
47TH ST.
44TH ST
HARRISON AVE. N.W.
38TH ST. N.W.
PUMPING PATTERN
1049
1050
1051
1052
1053
1054
1055
1056
1044
1043
1042
1041
1040
1039
1
2
3
4
5
6
7
8
9
10
WEST BRANCH NIMISHILLEN CREEK
LOG WELL
LOWER AQUIFER
UPPER AQUIFER
SCALE IN FEET
0
1000
JK

FIG. 2 – Contour map showing piezometric surfaces

contact with the stream and would obtain water from it to replace water pumped by wells. But the stream is intermittent and is dry during a fraction of the year. It would be necessary to draw from storage in the aquifer during about half of the time. The upper aquifer ranges in thickness from 20 to 40 ft and it can be shown that the useable quantity of water in storage is inadequate to assure the desired yield of 7000 gpm or ten million gallons a day.

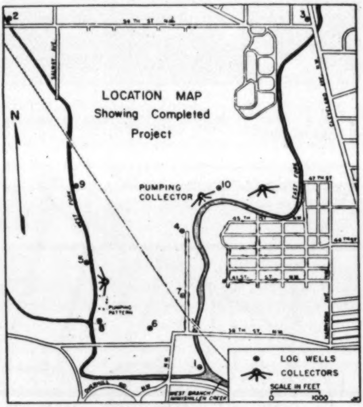


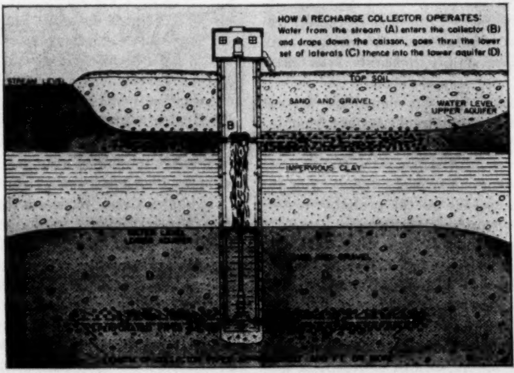
FIG. 3 – Relationship between the 'outriding' recharge units and the dual-purpose pumping unit

From an engineering viewpoint the deep aquifer, although it contains a tremendous amount of water in storage, had to be treated as a potential water-mine rather than as a reservoir because the rate and occurrence of recharge was unknown, and it was certainly not under the control of the City of Canton.

The technical problem thus resolved itself into finding a method of utilizing the upper, thin, aquifer as a filter plant and connecting it with the lower aquifer, which would then be transformed into a functioning reservoir. The negotiating problem was to convince the authorities in Canton that this was both feasible and worthwhile.

The solution to these problems was undertaken by Eugene Silitch (then President and Technical Director of Ranney Method Water Supplies) and the writer (who was at that time Chief Hydrologic Engineer of that Company). After many computations, which involved preparation of synthetic flow-duration curves, estimates of the filter-plant capacity of the stream bed under various conditions of head, and calculations of infiltration capacity, collector yield and interference, it became clear that the best technical solution would be to build three dual-purpose horizontal collectors and to equip only one of them with pumps. Figure 3 shows the relative position of the units. Pumps were installed in the middle collector, the other two serving solely for the purpose of recharge. Figure 4 shows how a recharge collector operates.

From a negotiating standpoint the problem was very difficult. The situation had to be presented so



HOW A RECHARGE COLLECTOR OPERATES: Water from the stream (A) enters the collector (B) and drops down the caisson, goes thru the lower set of laterals (C) thence into the lower aquifer (D).

FIG. 4 – Schematic cross section of the dual-purpose horizontal collector

clearly and conclusively that the city officials who possessed no familiarity with ground water, would agree to the construction of the two outriding collectors. These units, not having pumps, would not be of any visible benefit to the City. The negotiations, which amounted to a cram post-graduate course in the field of ground water were successful. The system was built as designed and has been operating for the past eight years to the entire satisfaction of all concerned.

This project illustrates how important skilled negotiating is to the successful accomplishment of technically complex ground-water projects. Without construction of the two outriding dual-purpose units, the project would have been of questionable value, with little assurance of maintaining the desired rate of offtake. Yet the position of the negotiators, confronted with the necessity of persuading responsible officials to approve the installation of two apparently useless horizontal collectors was an awkward one, because the value of the construction would not become manifest until a major dry period.

Conclusion—A scientific solution to almost any ground-water problem can be devised. An engineering solution, more difficult to achieve, is sometimes feasible. But the skills involved in negotiating and achieving a sound engineering solution are rare. There are no texts to study. A newcomer can only learn by example how to bring negotiations to a successful conclusion.

The future of the utilization of a region's water supply lies in the science, engineering, and negotiation needed to transform ground-water mines into ground-water reservoirs. There is much work to be done in all of these fields.

Stuttgart, Arkansas

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Upper and Lower Frequency Curves for Peak Rates of Runoff

W. D. POTTER

Abstract—Maximum annual peak rates of runoff plotted on extremal probability paper have many times been found to exhibit trends that may be defined by two straight lines designated as upper and lower frequency curves. Using a sample of 69 gaged watersheds with periods of record ranging from 26 to 48 years, a high degree of correlation is found to exist between the upper and lower frequency curves for 10- and 50-year recurrence intervals. Tests are made to show that these relations may be used in conjunction with periods of record as short as ten years to materially improve the precision of estimates of peaks on the upper frequency curve.

Evidence is presented that suggests that the dog leg in frequency curves is the result of sampling from two different populations of peak rates of runoff.

Introduction—It has often been observed by engineers and hydrologists who have had occasion to make probability studies of maximum peak rates of runoff that when these peaks are plotted on extremal probability paper they many times do not exhibit a straight line trend but rather one that is better defined by either a curve or by two straight lines. This dog leg (two straight lines) in the frequency curve is not limited to a few isolated locations but is quite general for streams located in the central and eastern portions of the country and is especially noticeable when the period of record is 25 years or more.

Upper and lower frequency curves—Figures 1 and 2 are two of the many illustrations of the dog leg in the frequency curve that might have been selected. The lower graph in each figure shows the maximum annual peaks for the entire period of record plotted on extremal probability paper. The right-hand branch of the dog leg, designated as the upper frequency curve, is the average curve for those peaks that have an indicated average recurrence interval equal to or greater than five years. Points on this curve are designated by subscripts such as Q_{10U}, Q_{25U}, etc. The numerical portion of the subscript indicates the average recurrence interval and the letter the upper frequency curve.

The left-hand branch of the dog leg, designated as the lower frequency curve, is the average curve for those peaks that have an indicated average recurrence interval of less than five years. Points on this curve are also designated by subscripts similar to those used on the upper curve except that the letter L replaces U to indicate the lower frequency curve as Q_{10L} or Q_{25L}.

Short records; a source of error—The upper graph on Figures 1 and 2, shows the frequency curve based on only ten consecutive years of record. For these short periods the dog leg is not apparent and the trend of the plotted points is one straight line. In Figure 2, the highest peak of 20,000 cfs was not considered in drawing the average frequency curve. This peak plotted so far off the line defined by the other nine peaks that it was assumed to have an average recurrence interval of approximately 200 years rather than the 11 years indicated by the theoretical plotting position. Note, however, that when the entire 29 years of record are used, this peak is consistent with the other peaks that define the upper frequency curve.

If it were assumed that only the ten years of record shown on the upper graphs were available and an estimate were desired of the 10- and 50-year peaks, they would have been those indicated by the average frequency curves. For the Sabine River, the estimate for Q_{10} would have been 113,000 cfs and for Q_{50} 168,000 cfs. If the entire record of 29 years had been available and the estimates taken from the upper frequency curve, they would have been 82,000 cfs for Q_{10U}, and 130,000 cfs for, Q_{50U}. The differences between, Q_{10} and Q_{10U}, and between, Q_{50} and Q_{50U}, expressed as a percent of, Q_{10U} and Q_{50U}, respectively, are measures of the errors that would have resulted from the use of the short term record. For the Sabine River, these errors would have been +38 pct for the estimate of the ten-year peak and +29 pct for the 50-year peak.

In a like manner, the errors of estimate for the 10- and 50-year peaks of the Flat River would have been, −9 and −28 pct, respectively.

Figures 1 and 2 illustrate the difficulties that are encountered when a sampling procedure is used to obtain estimates of peak rates from ungaged watersheds in any physiographic area. When short records are included in the sample of gaged watersheds to obtain peak rates for some reccurrene interval, errors of unknown sign and unknown magnitude are introduced. These errors may well obscure any relation that may exist between the true peaks for this recurrence interval and some independent variable such as watershed area. On the other hand, if only long records are used in the sample of gaged watersheds, the sample is apt to be so small as to be nonrepresentative of the area and watershed size groups being sampled.

Relations between frequency curves—If it could be shown that a high degree of correlation existed between the lower and upper frequency curves and if the lower frequency curve could be defined with sufficient accuracy by short-term records, then a way would have been found to increase the precision with which peaks having recurrence intervals equal to or greater than five years could be estimated from short periods of runoff records. More specifically, if a high degree of correlation existed between, Q_{10L} and Q_{10U}, and between, Q_{10L} and Q_{50U}, then this relation could be used in conjunction with values of Q_{10L}, determined from short records to provide estimates of the upper frequency curve. These estimates would have a known degree of accuracy provided the lower curves were sufficiently defined by the short runoff records.

To investigate this possibility, a sample of 69 watersheds was selected having periods of record of from 26 to 48 years and ranging in size from 3 to 6000 sq mi.

The maximum annual peaks for each watershed were plotted on extremal probability paper and the upper and lower frequency curves determined. Since the lower frequency curve, in most cases, was clearly defined by the plotted points, it was fitted by eye. The upper frequency curve, however, was a computed least-squares curve. From these frequency curves, values of Q_{10L}, Q_{10U}, and Q_{50U} were tabulated (Table 1). For each watershed, Q_{10L} was plotted against Q_{10U} on log-log cross section paper and an average least squares curve was computed for the 69 points. The equation for this curve is

$$\log Q_{10U} = 0.109 + 0.984 \log Q_{10L},$$

where Q_{10L} and Q_{10U} are expressed in 1000 cfs (Fig. 3). In a like manner values of Q_{10L} were plotted against corresponding values of Q_{50U} and an average least squares curve computed. The equation for this curve is

$$\log Q_{50U} = 0.273 + 0.985 \log Q_{10L},$$

where Q_{10L} and Q_{50U} are expressed in 1000 cfs (Fig. 3).

Both graphs show a high degree of correlation, 68 pct of the plotted points falling within ±10 pct error bands for the Q_{10L} versus Q_{10U} graph and within ±20 pct bands for the Q_{10L} versus Q_{50U} graph. It is estimated that these errors are approximately one-half to one-third those that might be expected if estimates of Q_{10U} and Q_{50U} were to be determined directly from single-frequency curves based on short periods of record.

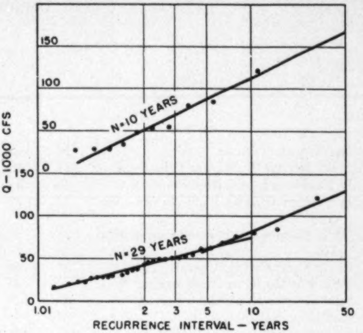

FIG. 1 – Frequency curves, Sabine River near Ruliff, Texas

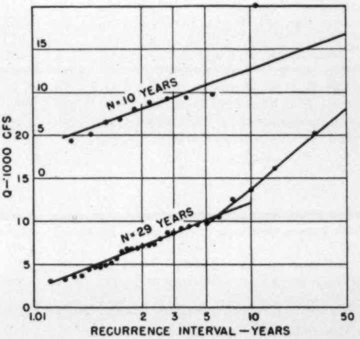

FIG. 2 – Frequency curves, Flat River at Bahama, N. C.

Use of relations to reduce error—Tests were now made to find the minimum length of record required to determine Q_{10L} with a sufficient degree of accuracy. Two 15-consecutive-year samples were selected from the record of each of the 69 watersheds. The beginning or end of these periods was determined by drawing a number from a stack of numbered cards. The number drawn indicated either the years of record that preceded

TABLE 1 – *Basic data*

Name and location	Record	Area	Q_{10L}	Q_{10U}	Q_{50U}	$\frac{\hat{Q}^{a}_{10U} - Q_{10U}}{\hat{Q}_{10U}}$	$\frac{\hat{Q}^{a}_{50U} - Q_{50U}}{\hat{Q}_{50U}}$
Piedmont Plateau							
	year	sq mi	Mcfs			pct	pct
Dial Cr. nr. Bahama, N. C.	29	4.9	0.79	1.03	1.47	−13	−9
N.Br. Raritan R. nr. Far Hills, N. J.	31	26.2	2.05	2.62	3.97	−12	−15
W.Fk. Deep R. nr. High Point, N.C.	30	32.1	2.83	2.76	3.35	14	29
Lamington (Black) R. nr. Pottersville, N. J.	32	32.8	1.08	1.29	1.77	−4	3
Little Gunpowder Falls at Laurel Brk., Md.	28	36.1	6.30	6.66	10.8	5	−6
Little Sugar Cr. nr. Charlotte, N. C.	30	41.4	6.40	6.48	9.01	9	15
S.Br. Roritan R. nr. High Bridge, N. J.	33	65.3	2.92	3.33	5.27	−1	−8
S.Br. Roritan R. at Stanton, N. J.	33	147	7.60	8.81	13.0	−4	−4
Flat R. at Bahama, N. C.	29	150	12.4	13.8	23.0	−1	−14
Blackwater R. nr. Union Hall, Va.	29	208	10.8	14.1	23.4	−18	−32
Slate R. nr. Arvonia, Va.	28	235	7.45	10.5	15.8	−27	−29
Appomattox R. at Farmville, Va.	28	306	11.2	14.5	22.1	−17	−21
Fishing Cr. nr. Enfield, N. C.	29	521	9.5	10.9	17.5	−4	−12
Roanoke R. nr. Toshes, Va.	29	1020	35.0	32.1	42.8	16	24
Rappahannock R. nr. Fredericksburg, Va.	39	1599	54.0	57.1	99.1	2	−15
Tallapoosa R. at Wadley, Ala.	31	1660	50.5	45.3	54.9	17	32
Roanoke R. at Brookneal, Va.	31	2420	68.0	74.4	138	−2	−27
Dan R. at South Boston, Va.	26	2730	40.2	57.3	97.4	−32	−51
Cape Fear R. at Lillington, N. C.	31	3440	64.5	85.5	131	−23	−27
Chattahoochee R. at West Point, Ga.	40	3550	77.5	79.6	128	4	−4
Horsepen Cr. at Battle Ground, N. C.	27	15.9	1.25	1.58	2.76	−10	−31
Missouri							
Fox R. at Wayland, Mo.	31	400	14.0	15.9	28.2	−3	−24
Wyaconda R. above Canton, Mo.	31	393	11.9	13.4	20.9	−2	−7
Salt R. nr. New London, Mo.	31	2480	46.3	48.0	63.3	4	15
Cuivre R. nr. Troy, Mo.	31	903	49.0	44.4	56.7	16	28
Nodoway R. nr. Burlington Junct., Mo.	31	1240	26.3	23.5	33.4	18	21
Pomme de Terre R. at Hermitage, Mo.	31	655	45.1	45.2	69.3	7	4
Meromec R. nr. Steelville, Mo.	37	781	40.0	43.3	67.0	0	−4
Bourbeuse R. at Union, Mo.	38	808	25.5	27.8	46.5	1	−13
James R. at Galena, Mo.	31	987	38.3	45.5	57.8	−10	6
Current R. at Van Buren, Mo.	31	1667	66.0	68.1	94.0	4	11
Current R. at Doniphan, Mo.	34	2038	63.2	61.6	95.0	9	6
Eleven Point R. nr. Bradley, Mo.	31	793	25.0	29.8	42.4	−10	−5
Ohio							
Little Beaver Cr. nr. E. Liverpool, Ohio	40	505	17.4	17.5	24.6	8	13
Kokosing R. at Millwood, Ohio	33	454	18.4	20.8	30.6	−3	−2
Licking R. at Toboso, Ohio	33	672	26.1	25.5	33.8	10	20
Hocking R. at Athens, Ohio	39	944	21.2	24.6	34.1	−6	1
Raccoon Cr. at Adamsville, Ohio	36	587	10.7	10.8	16.7	9	5
Big Walnut Cr. at Rees, Ohio	30	544	22.1	19.3	23.6	20	34
Alum Cr. at Columbus, Ohio	29	190	8.4	7.63	9.54	18	31
Darby Cr. at Darbyville, Ohio	32	533	18.9	19.2	32.0	7	−4
Little Miami at Milford, Ohio	29	1195	50.0	60.0	74.2	−11	7
Grand R. nr. Madison, Ohio	31	587	13.7	14.4	20.8	5	−7

TABLE 1 – *Continued*

Name and location	Record	Area	Q_{10L}	Q_{10U}	Q_{50U}	$\frac{\hat{Q}^a_{10U} - Q_{10U}}{\hat{Q}_{10U}}$	$\frac{\hat{Q}^a_{50U} - Q_{50U}}{\hat{Q}_{50U}}$
Iowa							
	year	sq mi		Mcfs		pct	pct
Maquoketa R. nr. Maquoketa, Iowa	37	1550	31.2	33.6	49.6	1	2
Cedar R. at Cedar Rapids, Iowa	48	6640	42.5	51.4	66.9	−12	2
Iowa R. at Marshalltown, Iowa	32	1530	20.0	22.4	42.2	−2	−30
Iowa R. at Iowa City, Iowa	48	3230	24.5	24.8	43.8	7	−10
Skunk R. nr. Ames, Iowa	26	322	4.80	5.48	9.40	−2	−18
Skunk R. at Cappock, Iowa	37	2890	28.2	30.9	47.2	3	−3
Skunk R. at Augusta, Iowa	36	4290	39.0	35.1	51.4	17	18
Raccoon R. at Van Meter, Iowa	36	3410	23.0	29.3	52.4	−17	−41
Ralston Cr. at Iowa City, Iowa	31	3.0	0.85	1.06	1.75	−8	−21
Illinois							
Pecatonica R. at Freeport, Ill.	37	1330	13.0	14.6	19.4	−2	9
Iroquois R. nr. Chebanse, Ill.	27	2120	20.0	21.2	31.6	3	3
Fox R. at Algonquin, Ill.	35	1364	4.70	5.42	6.35	−3	18
Mackinaw R. nr. Green Valley, Ill.	29	1100	19.5	21.7	29.2	−2	8
Spoon R. at Seville, Ill.	35	1600	22.7	25.3	37.7	−2	−3
Sangamon R. at Monticello, Ill.	41	550	11.5	12.4	20.5	2	−9
Cache R. at Forman, Ill.	28	242	7.75	8.45	10.3	2	19
Wisconsin							
Sugar R. nr. Brodhead, Wisc.	37	529	10.5	9.74	14.7	15	14
New York							
Little Towanda Cr. at Linden, N. Y.	38	22.0	1.60	1.60	2.26	12	16
W. slope Rocky Mountains							
Laramie R. nr. Glendery, Colo.	30	101	1.12	1.01	1.27	21	33
Buzzard Cr. nr. Collbran, Colo.	33	139	1.14	1.19	1.88	9	3
Laramie R. nr. Jelm, Wyo.	40	297	2.40	2.82	4.71	−4	−17
N. Fk. of S. Platte R. at S. Platte, Colo.	30	484	1.51	1.53	2.16	11	15
Dolores R. at Dolores, Colo.	33	556	6.79	6.79	9.49	10	15
White R. nr. Meeker, Colo.	40	762	4.65	4.73	6.31	9	18
San Juan R. at Rosa, N. Mex.	32	1990	12.6	15.9	27.2	−14	−32
San Juan R. nr. Blanco, N. Mex.	27	3560	18.7	20.9	28.3	−2	7

[a] Estimate from average curve.

the first year of the 15-year period or, if the remaining years of record were less than 15 years, the number drawn indicated the next following the last year of the 15-year period. For example, if the period of record were 30 years and the number five was drawn, the first year of the 15-year period would be the sixth year of record, the second year the seventh year of record, etc. If, however, the number 25 was drawn, the fifteenth year of the 15-year period would be the twenty-fourth year of record, the fourteenth year the twenty-third year of record, etc.

For each 15-year sample, estimates of Q_{10L} were determined by fitting by eye of average curves drawn through the maximum annual peaks plotted on extremal probability paper. In drawing these curves, only those peaks whose plotting position indicated an average recurrence interval of less than five years were considered. For each sample values of $\hat{Q}_{10L}$ (the estimates of Q_{10L}) were plotted on log-log cross section paper against the corresponding values of Q_{10U} and Q_{50U}, previously determined by least-squares curves based on entire periods of record.

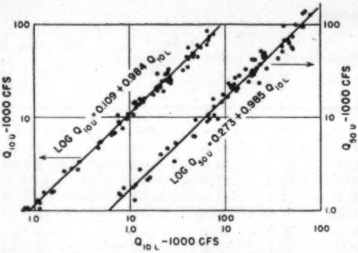

FIG. 3 – Relations between Q_{10L} and Q_{10U} and Q_{10L} and Q_{50U}

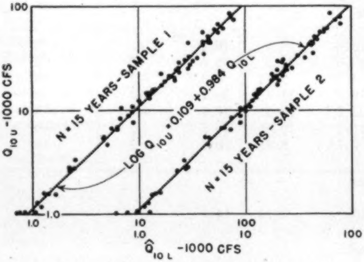

FIG. 4 – Relation between $\hat{Q}_{10L}$ and Q_{10U} for 15-yr samples

Figure 4 shows the, $\hat{Q}_{10L}$ versus Q_{10U}, graphs for each 15-year sample. The line drawn through each set of plotted points is the average least squares curve computed for the Q_{10L} versus Q_{10U} graph (Fig. 3), and based on the entire period of record. Since this curve is also a good average curve for both 15-year samples and since 68 pct of the plotted points for each graph falls within ±10 pct error bands, it was concluded that neither the relation between Q_{10L} and Q_{10U} nor the precision with which Q_{10U} could be estimated was altered materially by the use of 15-year records to define Q_{10L}. Likewise it was found that the precision that might be expected in estimating Q_{50U} and the relation between Q_{10L} and Q_{50U} as derived from the 15-year samples remained substantially the same as those computed from the entire periods of record.

In a manner similar to that described for 15-year samples, two ten-year and two five-year samples were selected and tested. For the ten-year samples, both the average curves and the precision that might be expected from estimates were found to be approximately the same as those computed from the entire record. For the five-year samples, however, it was found that, although the average curves remained unchanged, the precision that might be expected from 68 pct of the samples was decreased by approximately five per cent.

These tests would indicate that in physiographic areas where nearly constant relations exist between the upper and lower frequency curves, those relations may be used to advantage in conjunction with periods of record as short as ten years to improve the precision of estimates of peaks on the upper frequency curve.

Cause of dog leg—Two propositions are advanced to account for the dog leg in frequency curves. (1) The period of record is too short to define accurately the true recurrence intervals for the higher maximum annual peaks. (2) The samples of maximum annual peaks are drawn from two different populations.

If the first proposition were true, then the upper and lower frequency curves could be expected to become one and the same curve as the period of runoff record N were increased. Likewise, for any recurrence interval, the ratio of the upper curve value to that of the lower curve could be expected to approach unity as N became larger and larger.

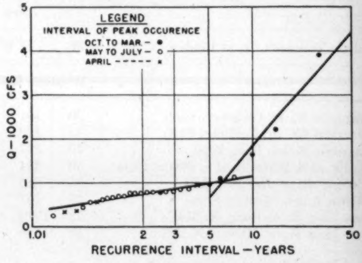

FIG. 5 – Frequency curves, South Fork Silver Creek near Ice House, Calif.

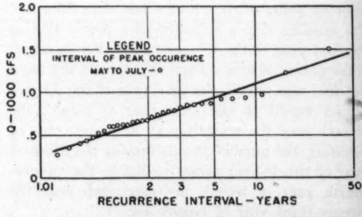

FIG. 6 – Frequency curve, Bear Creek near Vermillion Valley, Calif.

A partial test of the authenticity of this proposition was made with the 69 watersheds tabulated in Table 1. For each of these watersheds, values of the ratio of Q_{60U} to Q_{60L} were determined. The watersheds were then divided into three groups in accordance with the length of runoff record. The first group consisted of 23 watersheds whose period of record varied from 26 to 30 years. The second group contained 28 watersheds with periods of record varying from 31 to 35 years. The third group had 16 watersheds and periods of record varying from 36 to 40 years. The mean and standard deviation of the ratio of Q_{60U} to Q_{60L} for the three groups were as follows: Group 1, mean ratio = 1.18, standard deviation = ±0.29; Group 2, mean ratio = 1.17, standard deviation = ±0.22; Group 3, mean ratio = 1.22, standard deviation = ±0.18.

From the above comparison it is evident that there was no significant change in the ratio of Q_{60U} to Q_{60L} that could be attributed to a change in the period of record within the range of 26 to 40 years. The decrease in the standard deviation with an increase in N indicates a closer grouping of the ratio about the mean and is probably due to a more precise definition of the upper frequency curve as more upper curve peaks were included in the runoff record.

Although definite proof that the second proposition is invariably the true explanation of all dog legs in frequency curves is still lacking, one case will be cited where the second proposition undoubtedly did account for this phenomenon.

Twelve gaged watersheds located in northern California on the western slope of the Sierra Nevada were selected for study. These watersheds had uncontrolled surface runoff, ranged in size from 23 to 845 sq mi, and had runoff records of from 28 to 40 years. When the maximum annual peaks were plotted on extremal probability paper, it was discovered that ten of the 12 watersheds had a very pronounced dog leg in their frequency curves. The two exceptions had no dog leg at all, the frequency curve being one continuous straight line. Figures 5 and 6 are typical examples of these two types of frequency curves.

When the maximum annual peaks were classified as to the month in which they occurred, it was found that the large majority of peaks on the lower frequency curve occurred during the period May to July or during the month of April. Since little or no rain is experienced during May to July, those peaks that occurred during this period must have been caused by snow melt. Those that occurred during April could have been caused by rain or snow melt or by a combination of both. On the other hand, almost 100 pct of the peaks on the upper frequency curve occurred during the period of October to March and were the result of winter rains (Fig. 5).

The two watersheds whose frequency curves were single straight lines had average elevations of over 9000 ft. The maximum annual peaks all occurred during the period May to July and were the result of snow melt, (Fig. 6).

In this case there can be little doubt that the dog leg in the frequency curves was caused by the sampling of two populations, namely, peaks caused by rain and those caused by melting snow. Where the sampling was limited to only one population, peaks caused by snow melt, there was no dog leg and the frequency curve was defined by one straight line. This suggests that a similar phenomenon could result when peaks caused by either two different storm types (such as frontal and convectional) or by two different watershed conditions (optimum for high rates of runoff and intermediate for lesser rates) [*Potter*, 1949, 1951] are included in one sample.

Discussion—No attempt has been made in this paper to establish that the dog leg in frequency curves is a characteristic of all frequency curves of maximum peak rates of runoff or that the same correlation between the upper and lower frequency curves may be applied to all cases where the dog leg is found to exist.

Rather, an attempt has been made to illustrate that the presence of the dog leg is common to the frequency curves of watersheds in widely separated locations and that, where a high degree of correlation can be established between upper and lower frequency curves, it may be used to increase the precision of estimates based on short periods of runoff records.

Evidence has been presented that, although it does not definitely establish the cause or causes of the dog leg, lends weight to the proposition that it is the result of sampling from two populations of maximum annual peaks.

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A Long-Period Seismograph System*

FRANK PRESS, MAURICE EWING, AND FRANCIS LEHNER

Abstract—A matched three-component seismograph system operating with pendulum period of 30 sec and galvanometer period of 90 sec is described. As a result of increased sensitivity for periods greater than 20 sec, seismograms from these instruments contain information not previously available.

Introduction—The advantages of a seismograph system consisting of three matched components are well known. Instruments incorporating this feature were built by Galitzin, *Benioff* [1955], and Hiller. In this paper we describe a system of longer period than any of these, designed to improve the recording of seismic body and surface waves of longer period.

It is desirable to limit the response of such a system in the short-period range. This would minimize the response to microseisms (which limit the usable sensitivity of any seismograph system) and bring out long-period phases which are obscured by shorter period vibrations on standard seismograms. The major problem was that of constructing a stable vertical pendulum with a period of about 30 sec. A solution was found by using the zero-length spring principle of *La Coste* [1934] and the recently developed isoelastic spring materials, and by compensating for the buoyant effect of atmospheric pressure fluctuations.

Since 1951, a buoyancy compensated vertical seismometer [*Ewing* and *Press*, 1953] with periods of 15 and 90 sec for pendulum and galvanometer, respectively, has been operated at Palisades. The expected advantages of the instrument were quickly realized and, in addition, waves of several types, previously unknown, were recorded. In 1953, the matched horizontal components were added and the expected advantages again were soon realized. During the next few years, additional instruments of this type were installed in Bermuda, Pietermaritzberg, Perth (Western Australia), and Waynesburg (Pennsylvania).

Excellent results having been obtained in all cases, it was decided to make available a standard design of this seismograph system. This design was engineered by Lehner and Griffith, Inc., and is being manufactured by them as the Press-Ewing seismograph system. These instruments have been recording in Pasadena since 1956 with $To = 30$ sec, $Tg = 90$ sec, pendulum and galvanometer being critically damped. They will be operated at a number of stations during the International Geophysical Year.

Description—Figures 1 and 2 are photographs of the vertical and horizontal components, respectively. The glass sphere on the vertical pendulum serves as the buoyancy compensator. The upright is made of Invar for the vertical and of brass for the horizontal components. It is bolted to the pier through clearance holes in the base plate. The transducer is of the moving coil type, with a coil of 5000 turns of 34-gage magnet wire with total resistance 500 ohms. The magnet is made of Alnico V alloy with pole pieces arranged to produce a radial magnetic field of 2000 gauss.

The brass boom is 14¼ inches long and the inertial mass is 15 lb. The pendulum period is adjustable for stable operation in the range 10 to 30 sec. Damping of the pendulum is accomplished by shunting the coil, approximately 3800 ohms being required for critical damping for operation at a pendulum period of 30 sec. Sensitivity is adequate even when operated in a highly overdamped condition. Space is available on the base plate for installing an additional transducer, for example, to drive a second galvanometer or, after suitable amplification, an ink recorder.

All structural elements of the horizontal pendulum have equal coefficients of thermal expansion, the upright and boom being brass, and the suspension wire phosphor bronze. The boom length, inertial mass, transducer, free period, damping, and sensitivity are identical with those of the vertical.

The cover for each instrument is fabricated from sheet aluminum with a plexiglass window. All joints are sealed against draft with felt gaskets.

A Lehner galvanometer with free period 90 sec, coil resistance 500 ohms, critical damping, current sensitivity 10^{-10} amperes per millimeter

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* Contribution No. 842, Division of Geological Sciences of California Institute of Technology; Contribution No. 264 Lamont Geological Observatory of Columbia University.

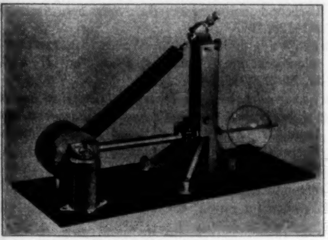

FIG. 1 – The vertical component seismometer

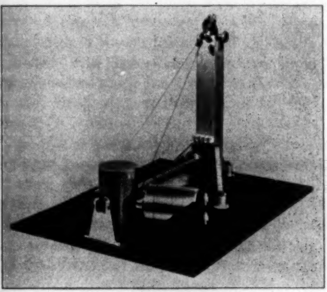

FIG. 2 – The horizontal component seismometer

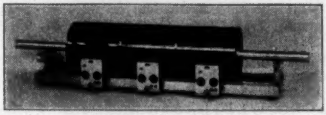

FIG. 3 – The triple component recording drum

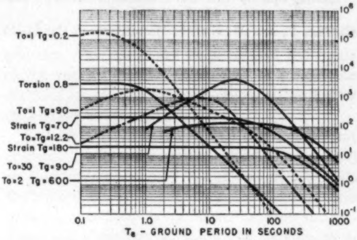

FIG. 4 – Calibration curves of various seismograph systems

deflection at one meter is connected to the transducer through a resistive network. The network provides for variation of damping and of sensitivity.

A triple drum recorder is used (Fig. 3), providing perfect alignment between the three seismograms, to facilitate comparisons of phases and determination of orbital motion.

The calibration curve of the instruments operating with pendulum and galvanometer at critical damping is shown in Figure 4. Also shown are curves for other seismographs currently in use. The method of calibration was essentially that of *Murphy* and others [1954].

The peak magnification of 4200 occurs for periods of 25 sec. The response diminishes rapidly for periods less than 25 sec and more gradually for longer periods. Owing to its superior magnification in the period range 20–200 sec, this instrument produces seismograms containing information previously unavailable.

Performance—Although primarily used for research, seismograms from this instrument have been surprisingly useful in routine analysis by providing clear recordings of later body phases, G waves, and the impulsive initiation of surface waves.

The recording of mantle Rayleigh waves from the great Kamchatka earthquake of November 4, 1952, made possible an extension of the dispersion curves for these waves as well as a determination of internal friction in the mantle [*Ewing and Press*, 1954].

Press and *Ewing* [1955] found clear indications of the new phases *Pa* and *Sa* on recordings of these seismographs. *Oliver* and *Ewing* [1957] reported on observations of unusually long-period microseisms.

These examples show how the new instruments have contributed to seismological research by providing increased sensitivity in a period range not covered by other seismographs.

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Shore-Based Recorder of Low-Frequency Ocean Waves*

FRANK E. SNODGRASS

Abstract—A pressure head on the sea bottom contains a hydraulic filter which attenuates high-frequency signals caused by ordinary gravity waves, and low-frequency signals caused by tides. Maximum response is for frequencies at about one cycle per 1000 sec. A strain-gage transducer converts the filtered pressure fluctuations into electrical signals, which are transmitted to shore through a cable.

Introduction—The instrument described in this paper was designed for the study of ocean waves whose frequency lies between those of the ordinary waves and those of the tides. Such low-frequency waves fall into two categories: (1) a low-frequency noise, which is always present and appears to be associated with meteorologic factors, and (2) tsunami waves, which arrive every year or two and are associated with earthquakes under the sea floor.

The existence of such low-frequency waves has long been known from ordinary tide-gage records, but these are not well adapted to record them, particularly the low-amplitude noise. In 1948 a pier-mounted gage with a three-stage hydraulic filter [*Munk*, *Iglesias* and *Folsom*, 1948] was installed at the end of Scripps Pier for the particular purpose of studying these waves. In 1952 a second instrument was installed at Oceanside Pier, 24 mi north of the Scripps instrument and connected to it by radio link. Subsequently a portable instrument for operation on remote islands was developed [*Van Dorn*, 1956] which employed a shore-based hydraulic filter connected to the sea by a tube or pipe. An instrument for offshore measurements from shipboard which employs a Vibrotron transducer and digital recording is discussed by *Snodgrass*, *Munk*, and *Tucker* [1958].

Description—Sea pressure is transmitted through a rubber bellows (Fig. 1 and 2). Two capillaries, R_1 and R_2, lead to two domes with metal bellows, C_1 and C_2. The rubber bellows, capillary tubing, and the compliant chambers between the dome and the outside of the metal bellows are filled with silicone fluid. The inside of the bellows and of the transducer chamber is filled with air maintained at atmospheric pressure. The total air reservoir is large relative to the bellows, and the variation in air pressure due to the deflection of the bellows is negligible compared to the changes in outside pressure. The transducer chamber and the inside of the bellows can be pressurized to extend the depth of installation, which is otherwise limited by the bellows to 10 m (one bar).

Two identical bellows are used in the compliant chambers, but the capillary tubes are adjusted so that their resistances to the flow of hydraulic fluid have a ratio of about four to one. A strain-gage pressure transducer is connected between the two compliant chambers to sense the differences in pressure. Because of the flow resistance of the capillary tubing, pressure fluctuations of very high frequency (ordinary waves) cause negligible pressure changes within the compliant chambers and between them. For pressure fluctuations of very low frequency (tides) the pressure in each chamber essentially equals the applied pressure, and the pressure difference between the chambers is again negligible. For intermediate frequencies the pressure in the two chambers is unequal owing to the difference in resistance of the capillary tubes, and an appreciable signal will be produced by the transducer.

Response characteristics—The equivalent electrical circuit of the pressure head is shown in Figure 2. Any arrangement of two resistors and two condensers to produce a band pass filter has a complex voltage attenuation of

$$e_0/e_i = A/(1 + jB) \tag{1}$$

For the particular arrangements shown in Figure 2, the constants have the values

$$A = (\beta - 1)/(\beta + 1) \tag{2}$$

$$B = \beta^{\frac{1}{2}} \, (k - 1/k)/(\beta + 1) \tag{3}$$

where

$$\beta = t_2/t_1 = R_2C_2/R_1C_1, \qquad t_2 > t_1 \tag{4}$$

$$k = f/f_0, \qquad f_0 = 1/2\pi\sqrt{t_1t_2} \tag{5}$$

t_1 and t_2 are the time constants associated with the circuit, f is the frequency of the applied signal, and

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* Contribution from the Scripps Institution of Oceanography, New Series No. 977.

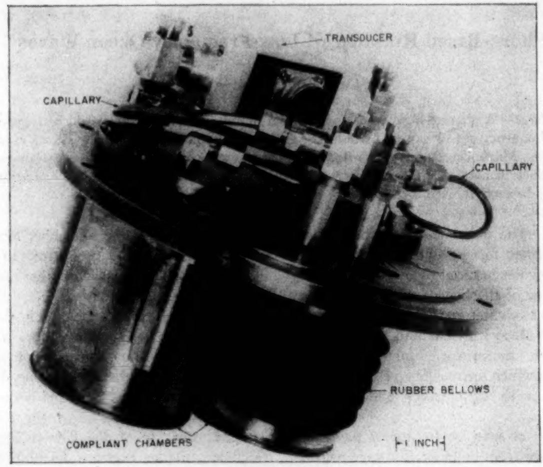

FIG. 1 – The pressure head assembly removed from its pressure case

f_0 is the center frequency of the filter. Thus the frequency response characteristics of this filter are described completely if the two time constants are known.

For a unit harmonic input, $\cos 2\pi ft$, the output can be written $r\cos(2\pi ft + \theta)$ where

$$r = \text{real part} \quad A/(1+jB) = A\cos\theta, \qquad \tan\theta = B \tag{6}$$

At the center frequency $k = 1$, $r = A$ and $\theta = 0$ (the output is in phase with the input). The half power points of the filter are at a frequency such that

$$k = (1/2\delta)[\sqrt{1+4\delta^2} \pm 1], \qquad \delta = \beta^{\frac{1}{2}}/(\beta+1) \tag{7}$$

The asymptotic behaviors are

$$r = Ak/\delta, \qquad \theta = 90^\circ \qquad \text{for } k \ll 1 \tag{8}$$

$$r = A/\delta k, \qquad \theta = -90^\circ \qquad \text{for } k \gg 1 \tag{9}$$

The frequency response curves in Figure 3 indicate results obtained using values of $\beta = 3.5$ and $f_0 = 1.37$ cycles/kilosec (730 sec/cycle). These values centered the filter in the low frequency band being studied and provided good attenuation of the signal produced by ordinary gravity waves and tides.

Calibration of the pressure head—The response of the pressure head is completely and conveniently described in terms of the two time constants, and relatively simple tests can be made to calibrate the pressure head. A step pressure input at time $t = 0$ (by suddenly lowering the pressure head through several inches of water) results in a transient response

$$x(t) = e^{-t/t_2} - e^{-t/t_1} \tag{10}$$

The time constants t_1 and t_2 can be determined from the measurements of the time t_m and the maximum amplitude x_m of the transient response

$$x_m = \frac{\beta - 1}{\beta}\beta^{-1/(\beta+1)}, \qquad t_m = t_2\frac{\ln\beta}{\beta - 1} \tag{11}$$

with $\beta = t_2/t_1$. The initial slope of the transient response curve

$$[dx/dt]_{t=0} = 1/t_1 - 1/t_2 = \ln\beta/t_m \tag{12}$$

can be used as a check.

Temperature effects—The principal temperature effect results from the linear dependence of the time constants, t_1 and t_2, on the viscosity of the oil. Results of calibrations at four temperatures are plotted in Figure 4. These data indicated that within the range of temperatures to which the instrument might be subjected, $\log t_1$ and $\log t_2$ decrease linearly with temperature; accordingly $\log f_0$ increases linearly with temperature. Since both time constants are affected proportionally,

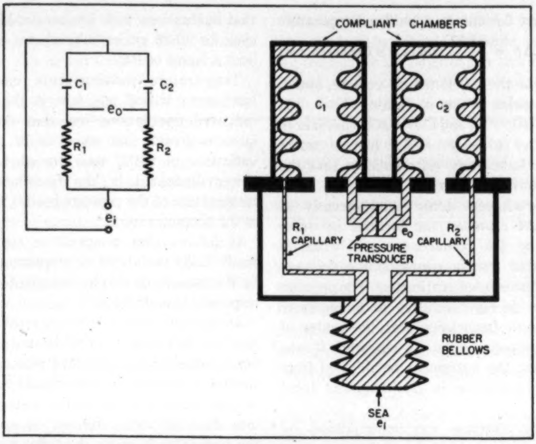

FIG. 2 – Schematic diagram of the hydraulic and equivalent electrical circuits of the pressure head; shaded region is oil-filled; remaining volume is filled with air

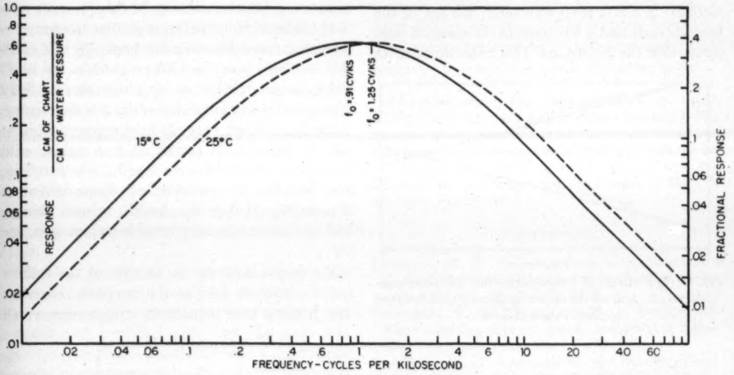

FIG. 3 – Amplitude response of the recorder; the right scale refers to the response r (Eq. 6) of the hydraulic filter; the left scale to the over-all response, including the electric components, which was used in obtaining the record shown on Fig. 5

the ratio of the time constants β is not affected. Thus the response curve (Fig. 3) is translated along the frequency axis. In our work it was necessary to allow for this effect in the interpretation of the instrument output, particularly at the high and low frequencies.

In addition to the problem involving the mean water temperature there are also output signals due to temperature transients. This effect arises on account of the differential expansion between the metal parts of the compliant chamber and the oil contained within these chambers, the oil expanding more rapidly than the metal container.

An estimate of the pressure change in the compliant chamber Δp due to a sudden temperature change ΔT is $\Delta p = \frac{\alpha V \Delta T}{C}$ where α is the coefficient of expansion of the oil, V the oil volume, and C the bellows spring constant. Setting $V = 100$ cm^3, $\alpha = 1.2 \cdot 10^{-3}$/°C, and $C = 0.036$ cm^3/(cm of water pressure) gives $p = 3.3$ (cm of water pressure)/°C. Laboratory tests indicate that the effect is somewhat smaller.

Since these changes occur simultaneously in both compliant chambers, an increase in water temperature by 1°C produces a signal which is indistinguishable from a corresponding decrease of water pressure of a few centimeters. The pressure head therefore is most sensitive to temperature fluctuations with frequencies near the center of the pressure response curve. In our work it was imperative that the instrument be shielded from temperature fluctuations in the frequency band of interest.

Temperature shielding was accomplished by burying the pressure head in the sand bottom to a depth of about one foot. If the test site did not have a suitable sand area, the pressure head was installed in a box filled with sand; the size of the box was such that a minimum of six inches of sand surrounded the instrument. This insulation assures that fluctuations with frequencies higher than one cycle/hr (0.28 cycles/kilosec) are reduced by at least a factor of 100.

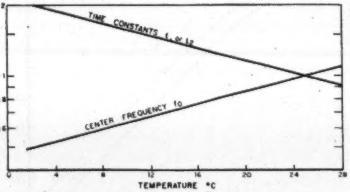

FIG. 4 – The effect of temperature on the time constants t_1, t_2, and on the center frequency f_0 all referred to their values at 25°C

Temperature measurements made with the instrument buried one foot in the sand bottom indicated fluctuations less than 0.01°C for frequencies greater than one cycle/hr, although daily variations of 0.5°C were recorded. The electric power dissipated in the transducer raised the temperature of the pressure head 0.5°C above that of the bottom water.

It follows that temperature signals are very small. Daily variations of temperature and heating by the transducer also have negligible effect on the response characteristics.

Mechanical features—In order that the pressure head can be buried in sand the unit is encased in a brass container and provided with a snorkel. The snorkel, a $\frac{1}{4}$-inch pipe, is shielded by an outer tube so that suspended material in water cannot settle into the instrument. Silicone oil was selected for the hydraulic fluid for the following reasons: (1) the oil is chemically inert and has excellent electrical properties which permit its use in the transducer, (2) the viscosity of the oil varies relatively little with temperature so that the temperature effects on calibration are small, (3) it is available at high viscosities (500 centistokes was used) which permit the use of large diameter capillary tubing and so minimize difficulties due to plugging.

Capillary tubes were made of copper tubing as follows: (1) 15-inch length, $\frac{3}{16}$-inch tubing with 0.125-inch ID, (2) $4\frac{3}{4}$-inch length, $\frac{1}{8}$-inch tubing, 0.062-inch ID. The metal bellows dimensions were: $2\frac{3}{8}$-inch OD, $2\frac{7}{8}$-inch live length, volume change, 2.25 in^3/bar; maximum allowable compression, one bar.

The space between the outside of the bellows and the dome is used as the compliant chamber. The bellows then remain in compression at all

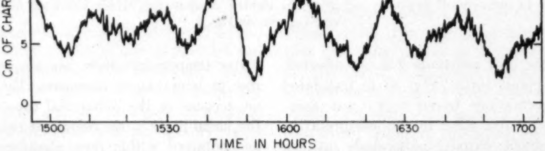

FIG. 5 – Sample wave record; vertical scale is in chart centimeters corresponding to the calibration curve, Fig. 3; the record, which is unusually active, was taken on Feb. 23, 1956, off Camp Pendleton, Oceanside, California

times and provide a nearly uniform spring constant. The arrangement permits the use of a small oil volume, and this in turn reduces temperature signals.

An important design consideration is that no air pockets should remain in the oil-filled portion of the instrument. The gage is filled with hydraulic fluid by removing the four pipe plugs in the hydraulic tubing (see Fig. 1) and connecting a reservoir of oil to these points. The unit then is installed in the brass housing and evacuated with a pump. Air contained in the complaint chamber, transducer, capillaries, etc., is drawn out. When atmospheric pressure is reapplied, the unit fills with oil. Any remaining air bubbles are absorbed by the fluid since most of the air normally in solution has been removed.

Electrical features—The pressure transducer must withstand many meters of water pressure during installation, yet be capable of sensing a millimeter of water pressure after reaching equilibrium on the bottom. A strain-gage transducer rated at 1.0 psi differential can withstand ±10 psi differential; the gage therefore can be lowered suddenly through 13.7 m of water without damage to the transducer. Equipped with a 2000-ohm, 31 v strain-gage element, it has a conversion factor of 0.9 mv/(cm water pressure) over its ±1 psi differential operating range. By connecting the gage output directly to a standard, self-balancing-potentiometer recorder, such as a Speedomax, overall recording sensitivities of the order of one centimeter of chart per centimeter of water pressure are readily obtained. Equivalent sensitivities were obtained without difficulty using d-c amplifiers and recording milliammeters, such as the Esterline-Angus.

Electrical power (30 v at 15 milliamp) was supplied to the gage from an electronically regulated power supply whenever 110-v a c power was available. At remote beach sites the gage was operated from wet cell batteries with a Speedomax recorder being driven by a 28-v d c to 110-v a c, 60-cycle converter. Thirty hours of operation could be obtained from four 6-v automobile batteries. Operating time can be greatly increased by using transistor amplifiers and spring-driven chart recorders.

Four-conductor cable is required for the bridge-type strain-gage transducer, while an additional two conductors are required if a thermistor circuit is used to indicate temperature of the pressure head. Cable lengths of several miles can be used providing leakage resistance between leads and between the cable and earth does not drop below about 0.1 megohm. Below these resistances the shunting effects or voltages generated due to sea water leakage may affect the readings.

Results—Several gages using the design described in this report have been used for three years with good results. Figure 5 shows an unusually active record. Ordinary gravity waves of 12-sec period (80 cycles/kilosec) are recorded with a response factor of 0.02 (chart cm)/(cm water pressure). These waves are responsible for the thickness of the trace. On the original record individual waves can barely be identified. For surf beat in the period band 1 to 4 minutes (4 to 16 cycles/kilosec) the response factor is between about 0.3 and 0.1. Twenty-minute-surges (0.83 cycles/kilosec) have a factor of 0.62. The tide, being reduced to 0.04 of its amplitude, is indicated as a slight drift in the record. The features here indicated can be resolved by a frequency analysis. A discussion will be given in a forthcoming paper.

Acknowledgments—The author wishes to thank Walter Munk for many helpful suggestions and Frank Peterson for his assistance in laboratory and field tests. This paper represents results of research carried out by the University of California under contract with the Office of Naval Research and the Bureau of Ships of the Navy Department.

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Offshore Recording of Low-Frequency Ocean Waves*

F. SNODGRASS, W. MUNK, AND M. J. TUCKER

Abstract—A Vibrotron transducer on the sea bottom converts pressure into frequency of a stretched wire. The oscillations are counted and recorded on shipboard in a form suitable for subsequent filtering and spectrum analysis by high speed digital computers. Oscillation by 1 mm of water pressure in the frequency range 0.2 to 100 cycles/kilosec (periods 5000 to 10 sec) have been recorded at depths exceeding 100 m.

Introduction—In the introduction to *Snodgrass* [1958] a brief account is given of the installation of pier-based tsunami recorders along the California Coast. In a sense these shore installations have been a disappointment. Tsunami waves appear to be so well reflected by the continental slope that relatively little wave energy reaches the shore installations. The result is that tsunamis are better recorded by the standard tide gage at Honolulu than by the special instruments along the California Coast.

The instruments did, however, provide interesting information about the day-by-day low-frequency noise, with the suggestion that this noise was in the form of edge waves traveling up and down the continental shelf and borderland. The principal characteristic of edge waves is that their amplitude diminishes rapidly seaward. To test this hypothesis the present instrument was built, and simultaneous measurements were made onshore [see *Snodgrass*, 1958] and offshore. The hypothesis was subsequently confirmed [*Munk, Snodgrass*, and *Carrier*, 1956]. By now more than 30 offshore stations have been occupied. The instrument promises to be useful also for the deep-sea recording of tides.

Our requirements are that the instrument should be capable of measuring waves with an amplitude of a few millimeters in the frequency range 0.1 to 10 cycles/kilosec, at depths exceeding 100 m. We first attempted to design a differential pressure gage, using air or springs as the compliant element. In the case of the air volume the instrument turned out to be a far better thermometer than a pressure transducer; the latter case called for special development of springs. A solution which easily met the above requirements turned out (perhaps surprisingly) to be an absolute pressure gage, using a Vibrotron pressure transducer, which converts pressure to frequency.

Pressure transducer—The Vibrotron pressure transducer [*Poindexter*, 1952; *Ohman*, 1955; *Prast* and others, 1955] was originally developed by the Southwest Research Institute, and is now being produced by B.-J. Electronics, Borg-Warner Corporation, Santa Ana, California. A pressure signal varies the frequency of a wire vibrating in a magnetic field. The induced voltage can be transmitted, recorded, or analyzed with all the advantages normally attributed to frequency modulated systems.

The vibrating wire is made of tungsten; the diameter is 0.025 mm and the length about 6 mm. It is stretched between the rigid structure and a small diaphragm exposed to pressure. The wire and its support is encased in an evacuated 2-cm dia cylinder 9 cm long, with electrical connections at one end, the diaphragm and pressure port at the other (Fig. 1). The wire is under tension of 15,000 to 20,000 bars. Increasing the pressure applied at the pressure port deflects the diaphragm inward, diminishes the tension, and decreases the natural frequency of the wire.

The wire vibrates in a magnetic field provided by Alnico V magnets with a field strength of 5,000 to 10,000 gauss and a gap of about 0.25 mm. This vibrating wire and a second, non-vibrating wire are connected in a bridge which is approximately balanced for d c. The output of the bridge, which is essentially the a c voltage induced in the vibrating wire, is amplified and fed back to the bridge in the sense required to maintain the wire in oscillation. The amplifier provides also for a sufficient power output (10 v across 100,000 ohms) to drive recorders or analyzers. Step-down transformers are used to match the output to low-impedance cables.

Transistor amplifiers—A thermionic amplifier matched to the Vibrotron transducer is available from the manufacturer, but this unit is not practical when power is supplied through long high-resistance cables. A transistorized amplifier was used which required only 4 ma at 20-v d c.

The amplifier circuit shown in Figure 2 (based

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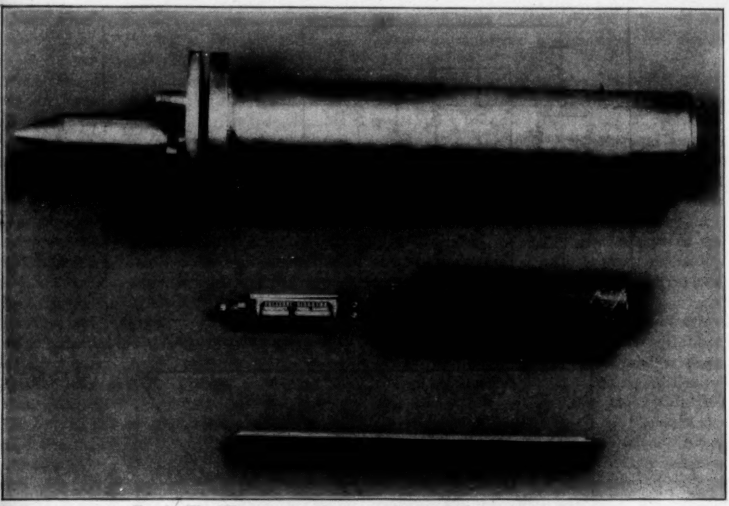

FIG. 1 – The Vibrotron transducer, transistor amplifier, and pressure case

on a development by *Snodgrass* and *Cawley* [1956]) has a gain of about 20,000 with an output of about 6 v. The resistance of the vibrating wire is low compared to the emitter load resistance, so that the Vibrotron can be connected directly to the first transistor amplifier. The second transistor acts as an impedance converter to reduce phase shifts resulting from the cut-off effect and the shunt input capacitance of the following transistor. The reduced phase shift of the amplifier, measured with the feedback condenser removed, is of the order of 60° and needs to be reduced still farther. The feedback condenser for each amplifier is adjusted by trial and error to produce zero phase shift at about 12 kc. The phase shift over the entire band 10 to 17 kc is then acceptable.

The complete system must have considerable frequency stability, since frequency is measured to one part in 10^6. This stability requires a constant amplitude of vibration of the wire. Effective amplitude control was accomplished by allowing the amplifier to overdrive in its last stage. The resulting distortion in the output wave form is not troublesome inasmuch as the recorded values depend only on zero axis crossings.

The amplifier was built as a potted plug-in unit with a diameter 3.8 cm and an overall length of 12.7 cm (Fig. 1).

Pressure sensitivity—We used two types of transducer, with the following characteristics:

Transducer	Pressure range		Frequency
	m	lb/in^2 abs	cycles/sec
Deep	0–750	0–1100	17,500–10,000
Shallow	0–180	0–250	17,500–10,000

A typical calibration for the shallow transducer is shown in Figure 3. The straight line is fitted to the equations $f^2 = -AP + B$ for $A = 1.26$ (kc/sec)^2/(m of water pressure) and $B = 317$ (kc/sec)^2. The pressure sensitivity $df/dP = -A/2f$ varies from 0.36 (cycles/sec)/(cm of water pressure) at zero absolute pressure to 0.64 (cycles/sec)/(cm of water pressure) at absolute pressure of 180 m of water (depth = 170 m).

Temperature sensitivity—The mechanical structure of the vibrating wire element is designed to minimize differential thermal expansion between the vibrating wire and the support structure for the wire. The manufacturer guarantees a temperature sensitivity of not more than 0.05 pct of the band width per degree Fahrenheit. For a transducer with a frequency band of 10,000 to 17,500 cycles/sec, the maximum response to temperature change by 1°C is then $0.0005 \times 7500 \times 1.8 = 6.75$ cycles/sec, which is equivalent to $6.75/0.36 =$

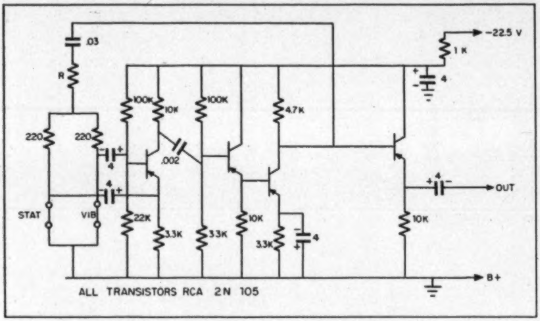

FIG. 2 – Schematic diagram of the Vibrotron transistorized amplifier

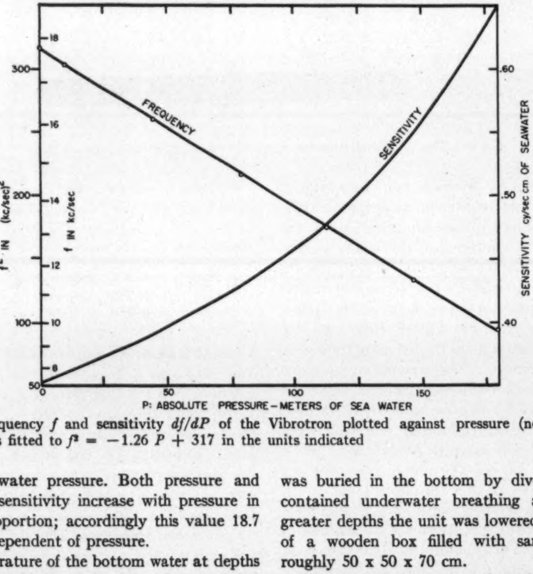

FIG. 3 – Frequency f and sensitivity df/dP of the Vibrotron plotted against pressure (not depth); the straight line is fitted to $f^2 = -1.26\ P + 317$ in the units indicated

18.7 cm of water pressure. Both pressure and temperature sensitivity increase with pressure in the same proportion; accordingly this value 18.7 cm/°C is independent of pressure.

The temperature of the bottom water at depths of several hundred meters may change rather suddenly by large fractions of a degree. In order for temperature 'noise' to be less than 1 mm of water pressure it is necessary that the temperature fluctuations of the Vibrotron transducer be less than that of the water by a factor of 100 for the frequency range of interest. This result was achieved by insulating the unit with moist sand. In water depths of less than 40 m the instrument was buried in the bottom by divers using self-contained underwater breathing apparatus. At greater depths the unit was lowered in the center of a wooden box filled with sand, measuring roughly 50 x 50 x 70 cm.

The theoretical response of a cylindrical box of compatible dimensions and filled with water (the role of the sand is to prevent convective heat transfer) indicates a reduction by a factor of 100 for a frequency of one cycle per hour (0.36 cycles/kilosec), by a larger factor at higher frequencies. The result was confirmed by comparing computed and measured response to a step change in temperature. In the laboratory the sand-insulated

Vibrotron was submerged in an ice bath, and at sea into the cold bottom water. Roughly 12 hr are required to reach equilibrium temperature (Fig. 4). In the case of tide measurement, the daily temperature variation of the Vibrotron had to be allowed for.

Stability—Various tests were performed with the Vibrotron and transistorized amplifier. A change of battery voltage from 22 v to 18 v altered the frequency by 0.1 cycles/sec. A change in the amplifier temperature from 25°C to 43°C decreased the frequency by 1.5 cycle/sec. Connecting a 1.0 mfd capacitor across the output transformer secondary (to simulate a long cable) decreased the frequency by 0.7 cycle/sec. A test of the over-all stability under ordinary working conditions is discussed under the heading *Noise spectrum*.

Digital recording—The pressure fluctuations of greatest interest in the present work have frequencies between 0.3 and 3 cycles/kilosec (periods between five minutes to one hour) and amplitudes of a few millimeters. Since the Vibrotron is an absolute pressure device, its output contains tides and ordinary waves, and these components are several hundred times the amplitude of the required signals. In the case of the shore-based recorder [see *Snodgrass*, 1958] the filtering of tides and ordinary waves is done pneumatically. Electronic filters were found to be unreliable at such low frequencies, but they were useful for monitoring the equipment during the tests. Our solution is to filter by numerical methods using high speed digital computers. Fortunately the output of the Vibrotron transducer is convenient for digital recording.

Commercial devices are available which count the number of cycles in a given time, using a quartz crystal clock to control the counting interval. This appears to be the most straight-forward and reliable means of recording. A Berkeley Scientific EPUT (events per unit time) meter equipped with a scanning and printing unit was used to tabulate the data on an adding machine tape. The timing interval can be selected as any multiple of one second up to 60 sec and is stable to one part in 10^6. A one-second time interval for the printing interval is also controlled by the crystal clock.

As an example, consider conditions summarized in the first line of Table 1. The shallow Vibrotron is very near the surface (absolute pressure about 10 m of sea water), and the oscillations are counted over a one-second interval. The sensitivity is 0.36 (cycles/sec)/cm water pressure, and hence a difference in count by one unit (say from 17,300 to 17,299) corresponds to 2.78 cm of water pressure. The last digit is in doubt, and hence this pressure equivalent of the EPUT least count is a measure of uncertainty.

The low precision is the result of dealing only with an integral number of cycles during a short time interval. There are two remedies. One is to deal with units smaller than entire cycles, such as half cycles, or third cycles, and this can be accomplished by multiplying Vibrotron frequency by

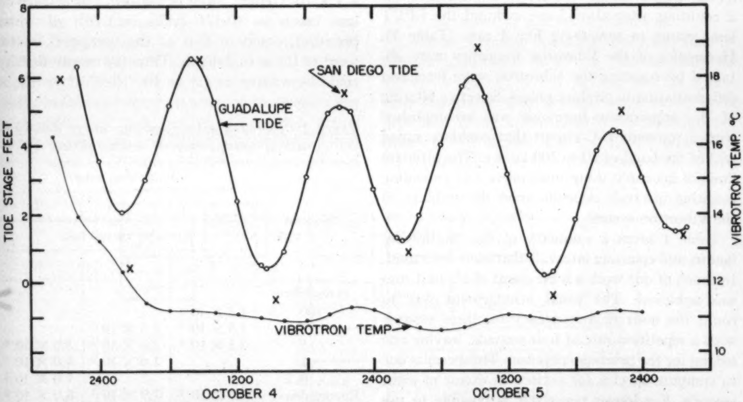

FIG. 4 – Tide and temperature data obtained at Isla de Guadalupe; gage installation depth 115 m; open circle points represent 5-min averages of uncorrected Vibrotron data; the measured Guadalupe tides were lower in amplitude and occurred earlier than predicted San Diego tides

TABLE 1 – *Digital recording least count*

Vibrotron range water pressure	Installed depth	Vibrotron Frequency	Vibrotron Sensitivity[a]	Multiplying factor	Counting interval	EPUT least count water pressure
m	m	kc/sec			sec	cm
0–180	0	17.3	0.36	1	1	2.78
0–180	0	17.3	0.36	5	3	0.19
0–180	100	13.3	0.47	7	3	0.10
0–180	170	9.6	0.65	10	3	0.051
0–750	0	17.5	0.08	5	3	0.83
0–750	400	14.0	0.10	7	15	0.095
				1	59	0.17
0–750	740	9.9	0.14	9	15	0.053
				1	59	0.12

[a] Cycles per second per centimeter of water pressure

two or three, and counting the mutliplied frequency. The other remedy is to count over intervals of time longer than one second. It is advantageous to do both; that is, multiply the Vibrotron frequency and count for several seconds.

The frequency of modulation and its amplitude (again in units of frequency) are both exceedingly small compared to the carrier frequency. Under these circumstances the multiplying factor is limited by the electronic counters. The equipment used has a maximum counting rate of 100 kc/sec. The multiplying factors used vary from 5 at shallow depths (Vibrotron frequency 17.3 kc/sec; EPUT frequency 5 × 17.3 = 86.5 kc/sec) to 10 near maximum depth (Vibrotron frequency 9.6 kc/sec; EPUT frequency 10 × 9.6 = 96 kc/sec). These multiplication factors, in conjunction with a counting interval of 3 sec, reduced the EPUT least count to something like 1 mm (Table 1). Harmonics of the Vibrotron frequency were obtained by squaring the Vibrotron wave form and differentiating to produce pulses. Selective filtering of the appropriate harmonic was accomplished with a resonant L-C circuit that could be tuned within the band of 80 to 100 kc/sec. The ultimate limit of accuracy using multipliers and extending counting intervals depends upon the stability of the Vibrotron system.

Table 1 gives a summary of the multiplying factors and counting intervals that have been used. In much of our work a least count of about 1 mm was achieved. The usual arrangement was to count the multiplied frequency for three seconds with a repetition rate of four seconds, leaving one second for the printing operation. This permits one to compute spectra for periods in excess of eight seconds. For longer periods it is possible to use longer counting periods, but this introduces the aliasing problem; if there is an appreciable signal component near the sampling frequency, the difference frequency will appear as a spurious low-frequency component. In our work this is a serious problem, because the low-frequency waves are so much smaller than the ordinary waves present. The safest procedure is to maintain the sampling frequency sufficiently high so that the bottom pressure fluctuations induced by waves of that frequency are essentially eliminated at the depth of the instrument [for further details see *Munk, Snodgrass*, and *Tucker*, in press]. For measurements of tides, and of the mean absolute depth, very long counting times are entirely appropriate.

The noise spectrum—There is no single number expressing the stability of the instrument. It depends upon the frequency under consideration. A convenient presentation is the energy (or power) spectrum of noise level. This was obtained by analyzing the output of a Vibrotron with a capped pressure port using just the same methods as for the actual wave measurements [*Munk, Snodgrass*, and *Tucker*, in press]. For temperature protection the capped Vibrotron and transistor amplifier were buried 120 cm in the sand bottom at a water depth of 8 m.

The result of three spectra is summarized in Table 2. The noise record from the capped instrument is interpreted in terms of equivalent pressure fluctuations on an uncapped instrument. The first line states that the contribution to the mean square pressure deviation of the record from the frequency band 99.5 to 100.5 cycles/kilosec equals 1.3×10^{-4} (cm of water pressure)^2. The sensitivity was taken as (0.372 cycles/sec)/(cm of water pressure), equal to that of the uncapped instrument at the actual depth. Thus the energy density could be written as $1.3 \times 10^{-4}\ (0.372)^2 = 1.8 \times$

TABLE 2 – *Vibrotron noise spectrum; energy density in (cm of water pressure)^2/(cycles/kilosec)*

Frequency	Multiplying factor 4	Multiplying factor 4	Multiplying factor 1
	Counting interval (sec) 3	Counting interval (sec) 14	Counting interval (sec) 60
cycles/kilosec			
100	1.3×10^{-4}		
25	1.5×10^{-4}	1.5×10^{-5}	
5	2.5×10^{-4}	2.3×10^{-5}	5.0×10^{-5}
1		1.6×10^{-4}	4.0×10^{-5}
0.2			1.0×10^{-3}
Energy density from least count	0.9×10^{-4}	1.9×10^{-5}	6.0×10^{-6}

10^{-5} (cycles/sec)^2/(cycles/kilosec), or 0.018 (cycles/sec)^2/(cycles/sec).

The last line gives the energy density of a white noise generated by a random variation of $\pm\frac{1}{2}$ count of the last recorded digit. For each test the high-frequency noise was at roughly this level, and thus the accuracy was limited by the EPUT counting rate (10^5 cycles/sec) rather than by the Vibrotron. (At high frequencies better results are obtained by reading off values from a continuous line record; see next section.)

In each of the three spectra the values rise for low frequencies. There is some evidence that this is due to temperature effects on the EPUT crystal. Thus within the range of frequencies covered by the noise spectra (periods 10 to 5000 sec) the present limitations appear to be imposed by the recording equipment rather than the transducer. But it must be emphasized that the over-all stability of the system is well within the exacting limits required by our work.

In addition there is a steady drift of frequencies which cannot be attributed to the recording system. This drift does not contribute appreciably to the frequencies covered by the noise spectra. The Vibrotron frequency increased by 0.37 (cycles/sec)/day (-1 cm of equivalent water pressure per day) at the beginning of a continuous 25-day test period. This drift rate diminished gradually and at the end of the test period was about two-thirds the initial rate.

Continuous line recording—A graphical record is very useful for monitoring while the test is underway. The graphical records were not used for analysis except at frequencies above 125 cycles/kilosec (periods less than 8 sec). At these high frequencies the electrical equipment is relatively stable and the limitation of the least count is avoided. In fact, we have recorded actual energy levels as low as 10^{-6} cm^2/(cycles/kilosec) at a frequency of 200 cycles/kilosec (period 5 sec) with the Vibrotron at 115-m depth off Guadalupe, using values read off the continuous Speedomax record.

The arrangement is indicated by the block diagram (Fig. 5). The multiplied frequency of the Vibrotron was heterodyned with a crystal oscillator, and the difference frequency converted to a voltage by a Hewlett Packard frequency meter. The voltage was filtered through a series of RC-circuits of very long time constant, and recorded on a multichannel Speedomax recorder.

The crystal oscillator unit was designed to provide an output signal that could be adjusted throughout the band of 80 to 100 kc/sec. This adjustment was accomplished by heterodyning dual temperature-controlled crystal oscillators operating near 5 mc/sec to produce a difference frequency within this band. Each of the oscillators was provided with ten crystals. The crystals of the first oscillator were cut at 2000 cycles/sec intervals, the crystals of the second oscillator cut at 200 cycles/sec intervals. The 100 combinations provided frequencies spaced at 200 cycles/sec. By means of a small variable condenser connected across the crystal in one oscillator it was possible to tune the difference frequencies by about ±200 cycles/sec so that any desired frequency could be obtained within the frequency band of 80 to 100 kc/sec.

The Hewlett Packard frequency meter provided an output of 1 ma in a 1300-ohm load resistance, or 1.3 v, for full scale reading. Thus on a 0 to 500-cycle band the conversion factor would be 1.3 v/500 cycles/sec or 2.6 mv/(cycles/sec).

Consider a typical operating condition. The Vibrotron is installed in 115 m (125 m abs); the average frequency is 12.7 kc/sec, and the Vibrotron sensitivity 0.50 (cycles/sec)/(cm of water pressure). Using a multiplier of 7, the frequency becomes 88.9 kc/sec and the EPUT sensitivity 3.5 (cycles/sec)/(cm of water pressure). A crystal

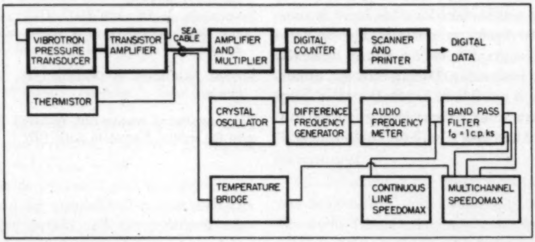

FIG. 5 – Block diagram of the low-frequency wave-recording system

oscillator frequency of 88.7 kc/sec provides a difference frequency of 200 cycles/sec. On a 0 to 500-cycles/sec band of the frequency meter, the average voltage is 200 × 2.6 = 520 mv, and the sensitivity 2.6 × 3.5 = 9.1 mv/(cm of water pressure). These values are reduced to 52 mv and 0.91 mv/cm respectively by using a 10/1 step-down attenuator. Now by recording on a 10-mv range Speedomax with a 0 to 100-mv biasing control, chart sensitivities 2.5 (chart cm)/(cm of water pressure) are obtained.

Rapid drifting due to tides and large fluctuations due to ordinary gravity waves are suppressed by means of band pass filters using biased electrolytic condensers. The condensers must be insulated against large temperature changes. Their leakage must be taken into account when evaluating the filter response. The condensers also exhibit a hysteresis effect (sometimes referred to as soaking). For the present purpose of obtaining qualitative results, the electrolytic condensers provide a simple and adequate means of obtaining the long-time constants.

Installations—The Vibrotron is placed on the sea bottom and connected with electric cables to the recording equipment. Cables up to three miles long have been used to connect the instrument to shore recorders.

There has been no entirely satisfactory solution for the case of shipboard recording. The instrument must not be disturbed by even one millimeter if the recording is to be of any use. One method is to employ the electric cable for an anchoring line. The Vibrotron is attached to a one-ton concrete weight. A second one-ton weight, separated from the Vibrotron by about 300 m of slack wire along the bottom, is intended to take the strain. For depths less than 150 m this arrangement has been satisfactory in reasonable weather. But in greater depths the ship motion resulted in a vibration of the cable which was transmitted to the instrument. In our early work we used 1500 m of 48 mm-dia armored cable and anchored a cable layer (a converted LCU) in depths up to 600 m. The development of an Amergraph cable 8.6 mm in diameter with a double reverse-lay 3175 kg-strength armor has now made it possible to handle the cable from a small research vessel. About 150 kg is added to the instrument and 100 m of 2-cm chain is lashed to the cable for holding power. An additional 15 m of 2-cm chain is lashed to the cable at mid-depth to provide spring anchor and to suppress cable vibration. Successful installations have been made in water depths up to 150 m.

For water depths of less than 150 m another method has worked out satisfactorily. The instrument was set on the bottom at a distance of about 500 m from the ship with the electrical cable floated across the surface. The section of cable between the surface and the bottom was kept taut by means of chain weights and submerged buoys. The ship was anchored by a conventional bow anchor, and could swing about her anchors without tangling the electrical cable and anchor wire.

For depths exceeding 150 m we now plan to try a third method. A taut electric cable is to be connected to a surface buoy, from which the signal is to be transmitted to the ship by radio link.

Acknowledgments—Frank Peterson has been very helpful on all stages of the development of this instrument. This paper represents results of research carried out by the University of California under contract with the Office of Naval Research and the Bureau of Ships of the Navy Department.

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A Fluid Level Sensing Device of Simple Design

REINHOLD GERHARZ

Abstract—A liquid-filled section of a coaxial conductor is used as a level sensing element, which changes the repetition frequency of a unidirectionally recycling electromagnetic pulse by subjecting it to various transit times. The deviations of the frequency are measured and provide a criterion for the height of the column of liquid in the sensing section of the feedback circuit. The device was tested with tap-water, acetone, and carbon tetrachloride.

Modern telemetering is characterized by the reproducible reduction of physical values into multiple analogues of electromagnetic constants. Among the numerous systems that find application in technology, only a few devices are in use in which the measured analogue values are disclosed as a variable frequency. With a recently described signal generator [*Gerharz*, 1956], the signal repetition frequency of which is the principal carrier of information, a very suitable application has been found for the sensing of fluid levels.

The main features of this generator are presented in Figure 1. The signal repetition frequency is primarily determined by the transit time of electrons in the amplifier tube (a type EFP 60 electron valve) and the propagation time of electromagnetic signals in the loop of the coaxial feedback conductor. With a one-tube circuit and various conductor lengths, a frequency interval from 2×10^6 to 5×10^7 cps has been covered.

It appears evident from Figure 1, that a coaxial conductor of a fixed length but with a variable impedance also will cause a change of the signal repetition frequency and that this frequency change is a function of the variable impedance. The experimental arrangement has utilized a column of tap water as a medium of variable impedance. This was accomplished by permitting the water to rise in the interior of a specially prepared section of the feedback conductor, thereby causing a change of the signal propagation time through the gage section. More explicitly, the time required for one signal to travel across the entire loop will then become

$$T_{\text{total}} = T_{\text{tube}} + T_{\text{conductor}} + T_{\text{gage}}$$

and with T_{gage} varying as a function of the fluid level h, the signal repetition frequency f_r will be described by $f_r = 1/T_{\text{total}} = f(h)$.

To insure stable operation and to suppress reflections, caused by mismatched connections between the gage section and the feedback conductor, it was found adventageous, to connect the inner conductor of the gage directly to the signal output of the generator. The voltage output in the case of the illustrated circuit was about five volts negative.

The gage resembles essentially a concentric system of two metallic cylinders of different diameters. The inner conductor is an insulated copper wire of about three mm diameter connected to the cathode of the amplifier tube, while the outer cylinder is a length of brass tubing of 12 mm in diameter at ground potential. The length of the gage section is about 150 cm. Both conductors are enclosed and mounted in a tube of glass, which communicates with the reservoir, the level of which is to be measured. Form and length of the gage section are not critical as long as it resembles electronically a coaxial system of medium attenuation.

In another device, a *U*-bent glass tube has been used, the outside of which was covered with silver paint. The inner conductor again was a thin copper wire drawn through the tube. Small vertical slits scraped into the silver coating provided visual access to the inside fluid level. The total length of the tube was about two meters. This construction also permits the determination of refractive indices of fluids and level metering of substances of high electric conductance [*Gerharz*, 1957]. The glass tube serves as insulator and container of the liquid.

In operation, the amplifier tube sends a sequence of very short pulses through the gage and the rest of the coaxial feedback cable. The pulse repetition frequency is determined by the only variable in the otherwise stable system: the fluid level in the interior of the gage. For precise measurements special efforts become necessary to stabilize the tube voltage and to screen the circuit effectively from undesired influence of heat and from electrical disturbances.

The detection of the pulse repetition frequency was accomplished with an ordinary radio receiver. The useful telemetering bandwidth depends on the total length of the feedback cable and on the

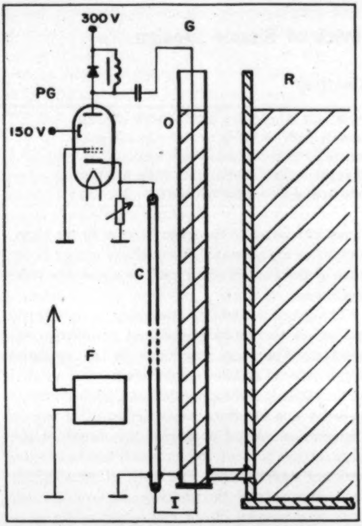

FIG. 1 – Schematic diagram of a fluid-level telemeter; PG, pulse generator; C, feedback conductor; R, reservoir; G, gage section; I, inner conductor; O, outer conductor; F, frequency meter

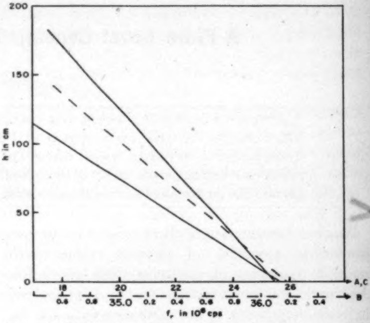

FIG. 2 – Calibration of a fluid-level telemeter with three metered substances; A, water; B, carbon tetrachloride; C, acetone

height of the gage. The emitted scattered field of the recycling signals is still large enough to be detectable some distance away from the device, even from well-shielded generators. Under the conditions leading to the representation of Figure 2, which shows relationship of the pulse frequency to the liquid level of three different fluids, a low quality short-wave receiver was still detecting the scattered signal at some 20 *m* distance from the gage. The range increased several fold in an open area after coupling a short antenna wire to the dynode of the amplifier tube.

Practical field applications for precipitation metering and for river- and well-level gages, however, would be operated more suitably, if the signal generator could pulse-modulate the amplitude of a small UHF-transmitter on a fixed carrier frequency. This would assist the control of several widely scattered automatically transmitting gage stations.

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Discussion of "Permeability and Infiltration Relationships in One Dimensional Infiltration in a Uniform Soil"

BY W. A. HALL

[*Trans.*, **37**, 602–604, 1956]

J. R. Philip (C.S.I.R.O. Division of Plant Industry, Deniliquin, N.S.W., Australia)—A rather complete mathematical physical method of studying problems of soil water movement is available and is capable of application to Hall's problem. I refer to the 'diffusion' approach, first suggested in concentration-dependent form by *Childs* and *George* [1948], used by *Klute* [1952] and later elaborated by the discusser [*Philip*, 1954b, 1955]. This is able to supply an integrated analysis of many isothermal soil-water problems [*Philip*, 1957e]. It involves numerical solution of a concentration-dependent diffusion equation which includes (in cases where gravity is important) an additional first order term. The problem of one-dimensional infiltraton in a uniform soil has been investigated in some detail. A brief account was given in *Philip* [1954b], and the work has recently received fuller publication [*Philip*, 1957abcd].

This is not to imply that there is no scope for an approximate analysis which may be much simpler and still represent the physical realities well enough to be useful for some purposes. A simple model which corresponds well to the experimental data of *Bodman* and *Colman* [1943], *Miller* and *Richard* [1952] and other workers has, in fact, been proposed by the discusser [*Philip* 1954a] and used by *van Duin* [1955] and *Hansen* [1955]. As presented, this simple analysis does not explicitly give the depth of the saturation surface as a function of time, but it is a straight-forward matter to deduce this for any particular numerical example. The relationship between this simple model and the more detailed 'diffusion' analysis is investigated in *Philip* [1957d].

Hall describes his hypotheses as 'restrictive'. In the discusser's opinion, the assumption that the hydraulic gradient in the 'transmission zone' is unity is entirely unreal. The data of Bodman and Colman, and of Miller and Richard reveal very large deviations from unit hydraulic gradient in the transmission zone. The magnitude of the deviations is shown by the following values of transmission-zone hydraulic gradients extracted from the experimental data of Miller and Richard. They are for ten minutes after infiltration began, except the Yolo loam, which is for 150 minutes: Yolo loam, 10; Tanbark sandy loam, 9; silica flour, 9; Hesperia sandy loam, 6. (Note that the arbitrariness of the bottom of the transmission zone and the fact that gradients were measured directly on the figures in the published paper lead to possible errors up to 20 pct in these values.) Bodman and Colman state that the decrease in infiltration rate with time appears to be due to "a decrease in moisture potential gradients resulting primarily from an increasing depth of penetration, that is to say, a vertical elongation of the transmitting zone." Hall, essentially, takes this gradient as zero from $t = 0$ onward and thus excludes from his model a vital aspect of infiltration dynamics. Detailed analysis [*Philip* 1957abc] bears this out and demonstrates that the assumption of unit hydraulic gradient would be acceptable only when t is so great that the infiltration rate has become sensibly constant.

Hall's equations (6) and (7) depend on the equality of K and K_t. However, experiment and physical reasoning indicate that if $K = K_t$, $\theta_s = \theta_t$, so that the terms under the square root signs of (6) and (7) are infinite and zero respectively. It might perhaps be argued that the equality of K and K_t should not be taken too literally, that K is essentially a parameter representing permeability in both zones and $(\theta_s - \theta_t)$ a second parameter representing the difference in storage capacity of the two zones. Even conceding this, we find that (7) gives the value $f = K$ (that is, a constant infiltration rate) for all $t > 0$ in the case, common in nature, when d is effectively zero. This paradox is inherent in Hall's use for all t of the long-time approximation that the hydraulic gradient in the transmission zone is unity. Incidentally, putting (1) in (4), setting $\Delta z/\Delta t$ equal to dz/dt, integrating for $K \neq K_t$ and using the condition $z = 0$ at $t = 0$ gives the following, which should replace (5) of the paper

$$\frac{z}{K - K_t} - \frac{Kd}{(K - K_t)^2} \times \log\left[1 + \frac{(K - K_t)z}{Kd}\right] = \frac{t}{\theta_s - \theta_t} \qquad (8)$$

A number of points arise in connection with Hall's relation of his experiments to his analysis:

(1) One must suppose that the legend of Figure 1 is in error, since (6) would give information about z, the depth of penetration of the saturation surface, not "the position of the wetting front."

(2) Further information about the experiments would be useful; for example, what was the value of d? (Applying (6) to the "calculated" line of Fig. 1, discusser deduces $d \approx 28$ cm.) How was the position of the saturation surface measured? Can runs 1–4 be identified on Fig. 1? Any data on f as a function of t for each run would be interesting. Note that, if (6) and (7) were to hold, $z/(f - K)$ would be equal to $2t/(\theta_s - \theta_i)$.

(3) z as computed from (6) is equally sensitive to all three of K, d, and $(\theta_s - \theta_i)$. In view of the uncertainties in K and $(\theta_s - \theta_i)$, it would seem that the only point at which Hall's published data might test his analysis is on the proportionality of z to $t^{1/2}$. The discusser has examined the effect of water depth on infiltration by the 'diffusion' approach; the work is reported in detail in papers at present in press elsewhere. The solution includes the result that at small t, z varies as $t^{1/2}$, but that the exponent increases with time. This clearly fits Hall's data better than his analysis does. By the way, the discusser finds that the three experimental lines on Figure 1 give exponents 0.70, 0.69, 0.61. The mean of 0.67 is appreciably greater than the 0.6 mentioned by Hall.

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Discussion of "A Correlation of the Characteristics of Great Storms"

by M. C. Boyer

[*Trans.*, **38**, 233–238, 1957]

Ven Te Chow (University of Illinois, Urbana, Ill., received June 13, 1957)—The writer is interested in the mathematics of storm characteristics as presented in this valuable paper, because he [*Chow*, 1953, 1954] has derived an equation for the average precipitation of practically identical form on the basis of similar assumptions. The writer has assumed that any observed storm pile can be converted into one which has circular horizontal sections, symmetrical with respect to the vertical axis of the pile and defined the storm pile as a three-dimensional representation of the rainfall isohyetals. By a mathematical treatment, a theoretical general equation for the average rainfall depth for all types of storms was developed. This equation is in the form of an infinite series

$$\bar{P} = a + bA^{0.5} + cA + dA^{1.5} + eA^2 + \cdots \tag{5}$$

in which $\bar{P}$ is the average depth of rainfall over an area A, and a, b, c, d, and e are coefficients.

The exponential term in (4) may be expanded into an infinite series as follows

$$\begin{aligned}\exp[-1.09(A/A_{0.5})^{0.5}] &= 1 - 1.09(A/A_{0.5})^{0.5} \\ &\quad + 0.594(A/A_{0.5}) - 0.216(A/A_{0.5})^{1.5} \\ &\quad + 0.059(A/A_{0.5})^2 - 0.013(A/A_{0.5})^{2.5} + \cdots\end{aligned} \tag{6}$$

Substituting (6) in (4) and simplifying

$$\bar{P} = 0.999P_{10} - 0.724P_{10}(1/A_{0.5})^{0.5}A^{0.5} + 0.297P_{10}(1/A_{0.5})A - 0.086P_{10}(1/A_{0.5})^{1.5}A^{1.5} + \cdots \quad (7)$$

This equation is practically identical in form with (5). Thus, $a = 0.999P_{10}$, $b = -0.724P_{10}(1/A_{0.5})^{0.5}$, etc.

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D. A. Kraijenhoff van de Leur (Landbouwhogeschool Wageningen, Netherlands, received August 6, 1957)—Before developing his basic relation between precipitation rate and area, Boyer refers to the Hydrometeorological Report 5 (U. S. Weather Bureau and Corps of Engineers, 1947). In the latter a proportionality is suggested between the precipitation rate along an isohyetal and the logarithm of the area enclosed by this isohyetal. Boyer inverts this relationship by introducing a proportionality between the logarithm of the precipitation rate and the area enclosed by the isohyetal concerned. Therefore Boyer's approach and the method developed in the Hydrometeorological Report 5 are based on different assumptions. It was felt that further verification of Boyer's basic assumption would be desirable.

Haeuser [1919] studied a great number of concentrated heavy summer storms in southern Germany. The observations of approximately 5000 stations covering an area of 76,000 sq km (30,000 sq mi) were used for drawing isohyetals for storms of high intensity which occurred in the years 1908–1915. The resulting rainfall patterns were used for checking Boyer's basic assumption by plotting log P against $R = (A/\pi)^{0.5}$, P being the precipitation rate on an isohyetal, A the area enclosed by this isohyetal and R standing for its mean distance from the storm center.

In each of the 28 cases studied it was found that the plotted points showed a systematic divergence from a straight line. An example is shown in the top of Figure 4. This divergence suggests that the rainhill's shape cannot be closely approximated by a simple relation between the precipitation at a certain spot and its distance from the storm center. Both Boyer's study and the Hydrometeorological Report 5 present such a simple relation.

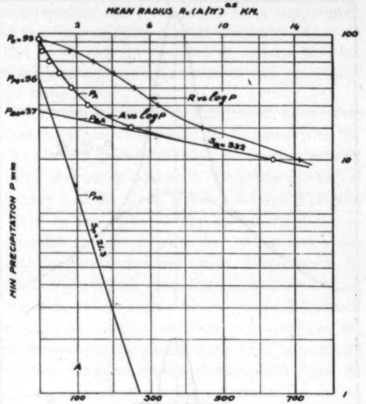

FIG. 4 – Graphical analysis of cloudburst near Jnzell, Germany, May 21, 1910, duration 1h 40m

During a recent study on intense summer storms the writer developed another approach, which results in a better approximation of the distribution of precipitation indicated by Haeuser's rainfall-patterns.

Analysing these patterns, the writer was led to the conclusion that nearly all intense rainfalls have a central core where extra heavy precipitation occurs.

Whatever its physical explanation may be, the concept of the rainhill being composed of a concentrated peak on top of a bottom storm that is relatively more wide spread and flat topped, appeared to lead to a close approximation of all investigated storm patterns. In order to find a mathematical formulation of this concept, it was assumed that the vertical cross section over the storm center can be approximated by two Gaussian curves superimposed on each other and centered on the same axis, as shown in Figure 5. Thus the precipitation P along an isohyetal with a mean radius R can be expressed by

$$P = P_{po}e^{-R^2/s_p} + P_{bo}e^{-R^2/s_b} \quad (8)$$

P_{po} and P_{bo} stand for the maximum totals of precipitation in the storm center, resulting from respectively the peak and the bottom storm, s_p and s_b are coefficients determining the spreading

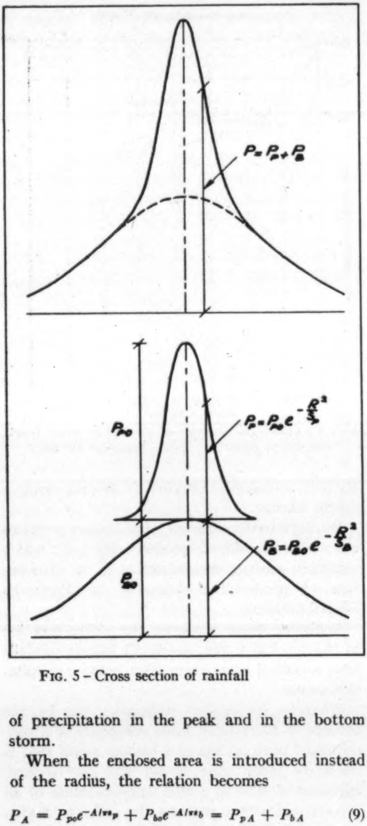
$P=P_p+P_B$
$P_p=P_{po}e^{-\frac{R^2}{S_p}}$
P_{po}
$P_B=P_{Bo}e^{-\frac{R^2}{S_B}}$
P_{Bo}

FIG. 5 – Cross section of rainfall

of precipitation in the peak and in the bottom storm.

When the enclosed area is introduced instead of the radius, the relation becomes

$$P_A = P_{po}e^{-A/\pi s_p} + P_{bo}e^{-A/\pi s_b} = P_{pA} + P_{bA} \qquad (9)$$

The precipitation along an isohyetal is plotted on a logarithmic scale against the enclosed area in rectangular coordinates and a curve is drawn through the plotted points. Then the diagram is split up into its components, the peak and the bottom storm, by drawing two straight lines in such a way that for any area the added ordinates P_{pA} and P_{bA} constitute a point on the curve of the relationship of A to log P. The intersections of these lines with the vertical axis mark the top values P_{po} and P_{bo} of respectively the peak and the bottom storm. The coefficients s_p and s_b can be derived from the declination of the straight lines.

By rotating and integrating the Gaussian distributions the following relation is found, giving the quantity of rain Q falling on an area A, enclosed by an isohyetal

$$Q = \pi s_p P_{po}(1 - e^{-A/\pi s_p}) + \pi s_b P_{bo}(1 - e^{-A/\pi s_b}) \qquad (10)$$

or

$$Q = \pi s_p(P_{po} - P_{pA}) + \pi s_b(P_{bo} - P_{bA})$$

The parameters s_p and s_b are known from the analysis and for any area A the values $(P_{po} - P_{pA})$ and $(P_{bo} - P_{bA})$ can be derived from the diagram. Q can be computed and consequently $\bar{P} = Q/A$.

It should be noted that $\bar{P} = Q/A$ introduced in (10) shows some resemblance with the result of Boyer's computations. The difference can be reduced to the following points: (a) The assumption of the Gaussian curve cross section which implies a proportionality between log P and the enclosed area A, instead of log P and the distance from the storm center as presented by Boyer. (b) The composite character of the rainhill against Boyer's simplified conception. Figure 6 shows the computed mean depth-area-curve. The general trend of this curve agrees with such curves as found by *Lott* [1953, 1954] both for a great storm of relatively long duration near Hallett, Oklahoma, and for a very intense small-area rainstorm near Holt, Missouri.

Recapitulating the comparison between Boyer's method and the one presented in this discussion: The latter produces a closer approximation of the distribution of rainfall when applied to the intense local storms, studied by Haeuser. As data on great storms are not available, the comparison between these two methods could not be extended to such distributions of rainfall as occur in extensive storms of long duration.

In hydrologic studies of small drainage basins

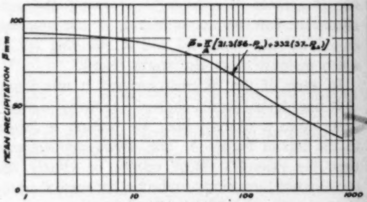

FIG. 6 – Mean depth-area-curve

and reclaimed areas thunderstorms are usually of major importance and in those cases the precipitation from a local peak may have a considerable effect on the resulting runoff. This effect will in many cases be amplified when the precipitation rate in the storm center is relatively high thus contributing even more strongly to the resulting direct runoff.

The solving of drainage problems in agricultural regions of the Netherlands therefore necessitates a thorough study of the characteristics of rainstorms, especially when a high watertable decreases the storage capacity of the soil. Consequently studies like Boyer's aiming at a numerical classification of rainstorms and using the considerable amount of precipitation data available in the United States, arouse great interest in this country.

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M. C. Boyer (Indiana Flood Control and Water Resources Commission, Author's closure)—It is interesting and gratifying to learn that studies of the characteristics of great storms by Chow led him to develop an equation of relation between average precipitation and area which is practically the same as (4).

Attention is drawn by Kraijenhoff to the fact that the author's results are not in accord with the formula for the distribution of average rainfall with area as presented in Hydrometeorological Report 5 of the U. S. Weather Bureau. This was noted by the author during his studies and considerable thought given to it. The conclusion was that the intense summer storm, convective in its origin and covering a small area, does not behave the same as the large cyclonic storm. Krajenhoff reached the same conclusion and considers the pattern of the convective storm to be represented by two Gaussian curves superimposed. Such an interesting pattern is unique, so far as the author is aware.

Excellent data on rainfall over small areas in Illinois have been collected by the *Illinois State Water Survey* [1957] which will be of considerable interest to engineers concerned with this problem.

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Discussion of "The Transport of Sand by Wind"

BY EDWIN F. FORD

[*Trans.*, **38**, 171-174, 1957]

R. A. Bagnold (Mark Beech, Edenbridge, Kent, England)—The simple Stokes law assumption appears to limit the applicability of the author's treatment to such fine dust particles as would in any case fail to describe the saltating trajectories indicated by Fig. 3. The reason for this failure is outlined in Jeffreys' paper under reference.

The fluid force on spheres of radius 0.0326 cm in the example given departs very appreciably from Stokes law. Taking the actual terminal fall velocity of such spheres as roughly typical of the wide range of resultant relative velocities obtaining during the whole trajectory, this is about 100 cm/sec (and not much different from that of real nonspherical grains of wide-blown sand). The fluid force on a sphere falling at this speed equals its own immersed weight, 0.33 dynes approx. The author's Stokes law expression (2) gives for the 100 cm/sec relative velocity a force of only 0.013 dynes. There is thus a 25-fold discrepancy due to the creation of turbulent eddies in the wake.

The Stokes law approximation might of course be justified on the assumption that the author's essential spin had the effect of inhibiting eddy formation. But this has not been established.

If approximate and workable equations of motion could be found for a single sand grain appropriate to conditions over the very awkward range of Reynolds number relevant, assuming some initial grain-free fluid velocity distribution, such equations may well be inapplicable to the simultaneous motion of many grains. For (a) the very appreciable influence of the moving grains on the fluid flow cannot be neglected [Bagnold, *Proc. R. Soc., A.*, **157**, 594, 1936], and (b) a typical grain path must include the effects of inevitable collisions between moving grains [Bagnold, *Phil. Trans., A.*, **249**, 235, 1956].

The problem is therefore more involved than the author's treatment would suggest.

Edwin F. Ford (3071 S. Woodrow St., Arlington, Va., Author's closure)—In the paper a number of simplifications of the problem were introduced. Of these perhaps the least tenable is the use of Stokes' law. It would possibly have been more appropriate to assume the drag to vary as the square of the relative velocity. As pointed out by Bagnold, an exact expression would have to take account of variations in the drag coefficient over a wide range of Reynolds numbers. This would considerably complicate the mathematics.

In the derivation given, a constant k is used in the expression for the lift, and so chosen as to give heights of trajectories about the same as those observed. A similarly adjusted empirical constant could have been included in the expression for the drag coefficient.

The sand-transport problem is certainly complex; this paper shows, however, that fairly simple equations can be set up which predict sand-grain behavior reasonably close to that actually observed.

Discussion of "Rainfall-Runoff Relations for Small Basins"

BY J. F. MILLER AND J. L. H. PAULHUS

[Trans., **38**, 216–218]

Louis A. Koffman (Corps of Engineers, Washington, D. C.)—The development of useful rainfall-runoff relations for small basins is an extremely useful extension of this valuable hydrologic tool. The authors are to be congratulated upon an excellent paper on an interesting subject presented in a clear and concise manner.

The writer is particularly interested in the subject because of his own efforts to develop some methods of computing approximate rainfall-runoff relations in various areas of the world, given a minimum amount of climatological facts and runoff data. In the course of the writer's investigations, he came to several conclusions which seem to be at variance, to some degree, with the authors'. Firstly, the authors state that experience has shown that the seasonal factor in the rainfall-runoff relation shows little change within a physiographically homogeneous region. The writer believes that authors may have meant to include similar climate as well as similar physiography. By definition, seasonal curves properly established should largely reflect the influence of the annual climatic cycle on runoff. In many areas of similar physiography, considerable differences have been known to exist in the evapotranspiration losses reflecting the effect of climatic differences. In place of accepting the seasonal curve from an area of one climate and using it for an area of another climate, the writer has obtained some workable runoff relations by adjusting the seasonal curves for variations in seasonal factors. The factors used included the mean air temperature in January and July, plus the length of the growing season and other climatic data. It seems to the writer, that if acceptable results were obtained by the authors in Georgia, using the seasonal curves of a rainfall-runoff relation developed in Maryland, the effect of differences in climate may have been only partially compensated in the hourly rainfall-hourly runoff portion of the runoff relation. If this were the case, the procedure illustrated in the paper will have limited application.

A further point which may need clarification is the adjustment made to compensate for change in the character of the drainage area at Little Falls during the period of record. The period of record at Bethesda, Maryland, used to develop the authors' rainfall-runoff relation, covers the period from 1946. As many people in the Washington area can attest, the watershed has experienced a phenomenal population growth. It is at present almost totally covered by a thickly-populated suburb of Washington, D. C., mostly built during the period of record. Such development must have affected the runoff relation in many ways. Certainly it must have destroyed the similarity between the Monocacy River basin, an area of low wooded mountains and rolling farm land, and the thickly-settled town of Bethesda which at present covers the watershed of Little Falls. In contrast to Bethesda, the Monocacy River basin has changed little during the last ten years. The increase of storm and domestic sewage at Little Falls plus the great increase of runoff from paved streets and roof tops are some of the most obvious changes which would affect the record of Bethesda.

The writer realizes that there are not many small drainage basins where the necessary data are available to enable the construction of a workable rainfall-runoff relation and that in any effort of this nature, compromise is necessary. However, he feels that a discussion of some of the necessary adjustments would add to the value of this useful paper.

J. F. Miller and J. L. H. Paulhus (U. S. Weather Bureau, Washington 25, D. C.; Authors' closure—The points raised by Koffman in his discussion show that he is well acquainted with the factors involved in the development of rainfall-runoff relations. The authors find no general disagreement between his views and theirs. Most of the apparent differences probably result from lack of adequate detail in the article.

In discussing the change with climate of the seasonal factor in the rainfall-runoff relation, Koffman is correct in presuming that the authors meant that there was little change within a climatologically and physiographically homogeneous region. This was not an omission but was due to the fact that the authors were referring to physiography in its broadest sense, which includes climate. Of course, there is no entirely satisfactory procedure for determining the climatic tolerances that can be permitted within a so-called climatologically homogeneous region. Admittedly, there is a general increase of precipitation from north to south in the region from New Jersey to Georgia, but there is also an increase of evapotranspiration. How much these variations would affect a rainfall-runoff relation for small basins is difficult to estimate.

In striving for brevity the authors made one omission that may have prompted some of the points raised by Koffman. They should have stated that the rainfall-runoff relations derived were for a special purpose. This purpose was to synthesize a record of annual flood peaks for a frequency analysis. Consequently, the rainfall-runoff relations needed to be satisfactory only for heavy, short-duration rainfalls that would normally produce the annual floods (the maximum peak discharge for each year) for basins no larger than a few square miles. This may explain in part why the man-made changes in the Little Falls basin during the period subsequent to 1946 may not have affected the results as much as one might expect. The difference between surface runoff from pervious and impervious surfaces is relatively less for intense rainfalls than for light or moderate rains. A time-trend study independently conducted for Rock Creek, also draining a suburban area of Washington, D. C., which has been highly developed during recent years, showed no appreciable changes in runoff characteristics.

The special purpose of the rainfall-runoff relations developed may also explain why satisfactory results were obtained without modification of the Monocacy River seasonal curves in the Little Falls relation. As Koffman states, reasonable differences would be compensated by a displacement of the rainfall curves, so that the runoff computations would be little affected. The limited application referred to by Koffman apparently includes the satisfactory estimation of runoff from intense local storms in the region from New Jersey to Georgia.

Discussion of "A Hypothesis of Formation of Mountains and Continents"

BY B. D. AGGARWALA AND EDWARD SAIBEL

[*Trans.*, **38**, 245–247, 1957]

Robert R. Wheeler (Meadows Building, Dallas, Texas; received May 16, 1957)—The authors have attempted to demonstrate mathematically that the cooling Earth suffered elastic failure primarily by "buckling rather than cracking" and that the resultant depressions localized the oceans while the humps formed the continents and mountains.

This conclusion ignores the few certain facts we know about the Earth's crust. It is readily observed that the continental crust has been repeatedly deformed by shortening accomplished by folding, faulting and loss of volume due to metamorphism. The oceanic crust shows no such tectonic pattern. It is profoundly different from the continental crust in strength, petrography, thickness, and elevation (reflecting its greater density).

In short, the continents could be described as light, granitic plates which terminate at the ocean borders and "float" within the same dense matrix that floors the oceans. The real problem is to determine how these light, continental plates were differentiated.

William A. Wiebenga (Bureau of Mineral Resources, Melbourne, Aust., received August 19, 1957)—The buckling suggested by the authors does not explain the basic difference in composition between the basaltic oceanic crust and the granitic or the metamorphic continental crust. Before buckling took place, the continents probably already existed.

Though the continental crust is usually considered as weaker than the oceanic part of the crust (implying that with mounting compressional stress it will break before the oceanic crust will), it is not certain whether it will buckle before the oceanic part of the crust will.

However, the geological evidence about geosynclines and mountain chains formed from geosynclines shows that the continental crust will buckle and break, often on the margin or boundary of continent with ocean, but that the main buckling movement is and must be downwards, and not upwards as the authors suggest. The mountain chains are formed at a later stage by compression of the sediments and vertical upwards movement to re-establish isostatic equilibrium.

The mechanism the authors describe mathematically may well be applied in a narrower sense to explain the formation of geosynclines. In that instance several checks on the mechanism may be suggested. For instance, after buckling the crust will crack by tensional stress on places where maximum bending moments occur. The cracks, accompanied by shears and faults, form excellent channels for subcrustal basic magma to rise to surface and near-surface level. This also explains the common association of basic dykes, basalts and dolerites with geosynclincal zones.

B. D. Aggarwala and *Edward A. Saibel* (Department of Mechanics, Rensselaer Polytechnic Institute, Troy, New York; authors' closure)—We are grateful to the discussors for their interesting remarks, and we are aware that the factors they bring up have not been taken into consideration. It was our intention to treat the problem quantitatively and in order to do this it was necessary, at the present time, to make very simplifying assumptions among which was that of homogeneity. The main purpose of the paper was to show the possibility of buckling as a mechanism for mountain formation. Having seen this possibility, it would now be of interest to consider a more realistic model.

Reviews, Abstracts, and Bibliography

Reviews and Abstracts

CLAYS AND CLAY MINERALS, PROCEEDINGS OF THE SECOND NATIONAL CONFERENCE ON CLAYS AND CLAY MINERALS, Edited by Ada Swineford and Norman Plummer, Nat. Acad. Sciences—Nat. Res. Council Pub. 327, 503 pp., 1954, $4.00.

This volume contains the 36 papers presented at the Second National Conference on Clays and Clay Minerals which was held at the University of Missouri, Columbia, Missouri, October 15–17, 1953. The topics embrace much of the field of clay research. There are six papers on genesis and sedimentary petrology, eleven on description and properties of clays, five on techniques, four on soils, and ten on physico-chemical studies of clays.

The approach to the study of clays in this book is largely geological, but geophysicists, particularly hydrologists and oceanographers, will find many of the papers of interest to them.

CLAYS AND CLAY MINERALS, PROCEEDINGS OF THE THIRD NATIONAL CONFERENCE ON CLAYS AND CLAY MINERALS, Edited by W. O. Milligan, Nat. Acad. Sciences—Nat. Res. Council, Pub. 395, 579 pp., 1955, $7.00.

The success of the National Conferences on Clays and Clay Minerals which are held annually is demonstrated by this volume which contains 43 original contributions. It differs from its predecessors chiefly in the shift of emphasis to physico-chemical studies of clay systems. There are 18 papers on physico-chemical studies of clays. The importance of electron microscopy in the study of clays is well illustrated in this volume. There are more than 50 full pages of electron micrographs, many of which are superb illustrations.

Both Volumes 2 and 3 are records of progress in clay research and represent the divergent types of study being made in this country. The papers reflect the changing emphasis in the study of clays and clay minerals. The National Research Council is to be congratulated for the fine workmanship which has gone into the publication of these volumes.

GEORGE T. FAUST

The Geological and Geographical Institute of The Academy of Sciences of the Lithuanian S.S.R., *Transactions of the Regional Conference on the Study of the Quaternary Deposits of the Baltic States and the Byelorussian S.S.R.* (in Russian), Scientific Reports; v. 4, edited by V. K. Gudelis with the collaboration of A. B. Basalykas, K. K. Bieliukas, M. M. Capenko, V. A. Cepulyte, E. F. Grinberg, A. I. Jaunputnin, and K. K. Orviku; 444 pp., maps, diagrams, cross sections, tables; State Publisher of Political and Scientific Literature, Lithuanian S.S.R., Vilnius, 1957; ca. $7.00.

This volume consists of 27 papers that were presented at conferences held in Vilnius and Kaunas, Lithuania, in November 1955. Geographically, ten of these deal with Quaternary phenomena in Lithuania, six in Estonia, five in Byelorussia, four in Latvia, and three deal with the Baltic area in general.

Subjectwise, there are ten papers on the stratigraphy of Quaternary deposits in these areas, six on geomorphologic features, two each on the structure of the deposits, paleogeography, fresh water calcareous deposits, extent and retreat of the ice, and erratics, and one each on pollen studies, geologic evolution during the Quaternary, distribution of ground water, and karst phenomena.

The volume is well illustrated with diagrams, maps, and cross sections, but the few half tones did not reproduce well enough to be effective illustrations.

The 27 papers, comprising the first 370 pages of the book, are not integrated by an index, but in the 49 succeeding pages four of the authors and 12 other participants of the conferences discuss some of the general as well as specific aspects of the papers.

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Notes and Personalia

Notes

Corrigendum—In the paper by R. O. Reid and K. Kajiura appearing in the October 1957 issue of the *Transactions,* pages 662–666, entitled "On the Damping of Gravity Waves Over a Permeable Sea Bed" the following corrections and changes should be made. On page 663, Eq. (2), change $-gh$ to $-gy$. In Eq. (3b), (13b), and (17), on the same page, replace p_2 by $p_2 + \rho g y$. These changes do not affect the rest of the development. Acknowledgment is made to Robert S. Arthur for detecting and reporting these changes.

Lowering of Permitted Level of Radiation Exposure—The Atomic Energy Commission has reduced by two-thirds the level of radiation exposure permitted for workers in atomic facilities in the Commission, people living near those facilities, and workers on atomic facilities of the contractors of the Commission. The new levels follow the recommendations made in January, 1957, by the National Committee on Radiation Protection and Measurement, which Committee noted that "changes in the accumulated maximum permissible dose are not the result of evidence of damage due to the use of earlier permissible dose levels, but rather are based on the desire to bring the maximum permissible dose into accord with the trends of scientific opinion." Under the new exposures, a worker may receive an average exposure of 5 rem (roentgen equivalent man), with a maximum in any one year not to exceed 15 rem.

Data Concerning the Underground Nuclear Explosion, September 19, 1957—The Atomic Energy Commission has announced the resultant yield of a deep underground nuclear test conducted in Nevada, September 19, 1957 as 1.7 kilotons. The shot was detonated at 16 hours 59 minutes 59.45 seconds GCT at the end of a tunnel 2000 ft long dug horizontally into the side of a mesa at the northern edge of the Yucca Basin in a layer of volcanic tuff. The coordinates of the detonation were 37° 11′ 44.8″ north, 116° 12′ 11.3″ west, elevation 6615 ft above mean sea level. The vertical distance from the detonation point to the mesa surface was 899 ft, and the slant distance to the side of the mesa was approximately 800 ft. Post-shot investigation of the tunnel and surrounding area confirm that the explosion was contained and that no radioactive materials escaped into the surrounding air. A detailed study of the area and the local effects of the detonation is in progress.

Meetings of the World Meteorological Organization—Regional Association III (South America) held its second meeting in Caracas, December 4–21, 1957. The group for the study on radiations of Regional Association I (Africa) met in Leopoldville, January 20–30. The Commission for Synoptic Meteorology held its meeting in New Delhi, January 21–February 14. The group for the study of sea ice of the Commission for Maritime Meteorology held its meeting in Washington, D. C., in February, 1958. The Joint ICAO-WMO Meeting on Telecommunications in Meteorology met in Geneva, February 24. Regional Association IV (North and Central America) will meet in Havana, March 18–28. Regional Association V (Southwest Pacific) will meet in Manila in April.

URSI Meeting—The U. S. National Committee for URSI combined with the Institute of Radio Engineers will hold their spring meeting at the Willard Hotel in Washington, D. C., April 24–26, 1958. Inquiries should be addressed to the U. S. National Committee for URSI, c/o National Research Council, 2101 Constitution Avenue, N.W., Washington 25, D. C.

RAIN-DISPERSING IN NORWAY—Experiments are under way on the west coast of Norway in an effort to reduce the rainfall in these regions. Initial results have been encouraging. Seeding with silver iodide has been successful in preventing humidity from condensing into raindrops long enough for the wind to blow the moisture elsewhere. There is the hope that this may be effective in dispersing the clouds in the lowlands and that they will finally gather and shed their rain over the higher mountainous regions inland, increasing the water supply for hydroelectric stations and giving aid in other regards in the economy of the country.

FELLOWSHIPS AND RESEARCH ASSISTANTSHIPS AT TEXAS A. AND M.—The Department of Oceanography of the A. and M. College of Texas has available fellowships and research assistantships to qualified holders of baccalaureate degrees for the academic year 1958–1959. There are three fellowships with stipends ranging from $1800 to $3000 and research assistantships ranging from $1800 to $2775. Matriculation and other fees, board, room rent, and laundry approximate $600 for the academic year and additional fees for out-of-state students of $150 a semester. Application forms may be secured from the Department of Oceanography and Meteorology, A. and M. College of Texas, College Station, Texas.

RESEARCH CENTER OF THE OHIO OIL COMPANY—The Ohio Oil Company now has work under way to complete the initial building program of its Research Center at Littleton, Colorado. Two new wings are being constructed, resulting in a 60 per cent increase in area to a total of about 70,000 square feet. The Laboratory is under the direction of W. Jack Yost.

DEDICATION OF THE COASTAL ENGINEERING LABORATORY AT GAINESVILLE, FLORIDA—This dedication was held December 3, 1957, in connection with the Coastal Engineering Congress that drew some 200 participants from thirteen countries. Per Bruun is the Director of the Laboratory.

PLANS FOR NATIONAL HURRICANE RESEARCH PROJECT—The U. S. Department of Defense has agreed to continue support of the U. S. National Hurricane Research Project through the hurricane season of 1958. One USAF B-47 Stratojet and two USAF TB-50 Superforts will be available.

NEW FINDINGS IN THE GULF OF ALASKA—The Coast and Geodetic Survey has announced the discovery of a deep, long trough in the bottom of the Gulf of Alaska which may be involved in tidal waves originating in that region. The chasm is 500 to 700 feet below the ocean floor and about two to three miles wide, stretching in a southwesterly direction across much of the Gulf below southern Alaska and is known to be at least 250 miles long.

NATIONAL SCIENCE FOUNDATION GRANTS—The National Science Foundation has recently announced 316 new grants totaling nearly $5,500,000 awarded during the quarter ending September 30, 1957. This brings the total grants since 1951 to 4,179, and the amount granted almost $66,000,000.

CONTINUANCE OF TEACHER TRAINING PROGRAM—The National Science Foundation is continuing its program in teacher training and will hold 108 institutes this coming summer at a cost of over $5,000,000. The Atomic Energy Commission is jointly sponsoring twelve of the institutes where courses in radiation biology for high school teachers are offered. It is expected that 5000 high school teachers and 250 college teachers will take the courses. Most institutes will pay a weekly stipend of $75, with additional allowances for travel and dependents. The program was started in 1953 with two institutes; in 1957 there were 96 institutes. A list of the institutions and which courses will be given may be secured from the National Science Foundation, but application for admission to the institutions must be made to the individual institution.

GRANT FOR SUPPORT OF HIGH-ENERGY PHYSICS—The National Science Foundation has made a grant of $160,000 to the Midwestern Universities Research Association (MURA) of Madison, Wisconsin, for basic research on high-energy accelerators with energies involving billions of electron volts. This grant is the seventh made to MURA for support of studies in this field. The new grant supplements funds received from the Atomic Energy Commission.

The Midwestern Universities Research Association is a group of 15 Midwest Universities which formed this Association in 1953 for research in high-energy physics and includes the following universities: Chicago, Illinois, Indiana, Iowa State College, State University of Iowa, Kansas, Michigan State, Michigan, Minnesota, Northwestern, Notre Dame, Ohio State, Purdue, Washington University (St. Louis), and Wisconsin. H. R. Crane of the University of Michigan is its president.

INTER-REGIONAL TRAINING SEMINAR ON HYDROLOGIC FORECASTING AND WATER BALANCE—This seminar was held at Belgrade, Yugoslavia, October 28 to November 16, 1957, and was sponsored by the World Meteorological Organization and the Hydrometeorological Institute of Yugoslavia. There were 28 participants from 19 countries. G. A. Alekseev of the Hydrometeorological Institute of the USSR presented a series of lectures on use of statistical methods in hydrology and G. P. Kalinin of the same organization discussed methods of flood routing. J. R. Mather of the Laboratory of Climatology of the Drexel Institute presented material on the water balance and Ray K. Linsley of Stanford University discussed techniques of flood forecasting used in the United States. C. W. Thornthwaite of the Laboratory of Climatology at Drexel was present for the first week and discussed the problems of water balance. Following the seminar, a five-day study tour of northern Yugoslavia was held, this permitting participants and lecturers to study stream gaging and sediment sampling in Yugoslavia.

NEW SWEDISH GEOPHYSICAL OBSERVATORY—The new Kiruna Geophysical Observatory of the Royal Swedish Academy of Science was formally opened July 2, 1957, upon the completion of the main observatory building and the ionospheric laboratory. This represented a culmination of a decade of planning and development. The Observatory is located in northern Sweden at 67.8° N, 20.4° E (geomagnetic, 65.30° N, 115.5° E). This bears an interesting relationship to the Geophysical Institute at the University of Alaska, with which it will cooperate closely. The Geophysical Institute is 64.9° N, 147.8° W (geomagnetic, 64.5° N, 104.6° W). A grant from the National Science Foundation aided in the equipping of the Observatory. Bengt Hultqvist is the Director at Kiruna. Attending the dedication ceremonies from the United States were Lloyd V. Berkner and J. Wallace Joyce.

MEETING OF SCOR—The Special Committee on Oceanic Research (SCOR) set up within the framework of the International Council of Scientific Unions held a three-day meeting at Woods Hole Oceanographic Institution in late August 1957 to lay plans for the future. It was noted that the three problems most in need for long-range studies included productivity of the sea, the ocean as a disposal area for industrial pollution including radioactive wastes, and the role of the ocean in climatic changes. Tentative plans were laid for future work including an expansion of deep-sea observations (the techniques for which have been improved greatly in the last few years) involving theoretical studies and further development of techniques, and a multiple ship operation in the Indian Ocean where a few oceanographic vessels have undertaken work, none using modern techniques. When the difficulties of observation techniques at great depths are overcome and the problems of accurate navigation are solved, probably large quantities of artificially radioactive material could be released in the ocean for tracer studies of the circulation of water masses. SCOR includes Roger Revelle, Chairman; G. E. R. Deacon, Vice-Chairman; G. Böhnecke, Secretary; and the following members: Anton Bruun (Denmark), L. R. A. Capurro (Argentina), Y. Miyake (Japan), L. Zenkevitch (USSR), M. N. Hill (England), H. Mosby (Norway), E. Steemann Nielsen (Denmark), N. B. Marshall (England), Y. LeGrand (France), N. W. Rakestraw (USA), and C. O'D. Iselin (USA).

NEW COMMITTEE ON OCEANOGRAPHY ESTABLISHED—A new Committee on Oceanography to serve especially the needs of the Fish and Wildlife Service, the Department of Defense, and the Atomic Energy Commission has been established in the Earth Sciences Division of the National Academy of Sciences-National Research Council. Chairman of the new Committee is Harrison Brown. The other members are: Maurice Ewing, C. O'D. Iselin, Fritz Koczy, Sumner Pike, Roger Revelle, Gordon A. Riley, Milner B. Schaefer, and Athelstan Spilhaus, with Richard C. Vetter serving as Executive Secretary.

CRUISES OF THE SCRIPPS INSTITUTION OF OCEANOGRAPHY—The second of three IGY cruises of the Scripps Institution of Oceanography will depart from San Diego, March 27, 1958. The purpose of this cruise is to study ocean currents in the vicinity of the Equator, particularly their Equatorial Undercurrent. The Scripps vessel *Horizon* will be joined in the work at the Equator by the *Hugh M. Smith* of the Pacific Oceanic Fishery Investigations. They expect to return about June 9.

The third IGY Cruise will leave San Diego on August 1 and will involve three Scripps vessels, *Horizon*, *Baird*, and *Stranger*, and possibly will be joined by a frigate from Colombia. The purpose of this cruise is to study short-period fluctuations in the Equatorial Countercurrent, the center of which is near 8° N, 110° W. The return to San Diego is scheduled for September 30.

NEW GRADUATE COURSE IN HYDROLOGY AT CLARK UNIVERSITY—Clark University is giving a new graduate seminar in the geographic aspects of hydrology. The seminar is being conducted by David H. Miller of the Quartermaster Research and Engineering Center at Natick, Massachusetts.

NEW SPACE TECHNOLOGICAL LABORATORY—The Ramo-Wooldridge Corporation of Los Angeles has announced the establishment of a Space Technological Laboratory as an outgrowth and extension of its Guided Missile Research Division.

SURFACE MEASUREMENTS OF GRAVITY AT SEA—Lamont Geological Observatory has announced that recently surface measurements of gravity at sea were made using a new sea gravimeter developed by Anton Graf of Germany. The instrument was mounted on a platform stabilized by a gyroscope aboard the *U.S.S. Compass Island*. The work was under the direction of J. Lamar Worzel.

NEW ANTARCTIC PUBLICATION IN ARGENTINA—Volume 1, Number 1, of the ***Boletin del Institute Antartico Argentino*** was issued under date of May 1957 by the Antarctic Institute of Argentina of which Rodolfo N. Panzarini is the Director.

NEW EARTH SCIENCES DEPARTMENT AT STANFORD RESEARCH INSTITUTE—Recognizing the growing emphasis on research in various aspects of the Earth sciences, Stanford Research Institute has established a Department of Earth Sciences in its Physical Sciences Division under the Chairmanship of Richard M. Foose, formerly of Franklin and Marshall College. This Department will deal especially with the hard-rock and mineralogical aspects of the geophysical sciences.

NEW OPTICAL ASTRONOMICAL OBSERVATORY—The Association of Universities for Research in Astronomy (AURA), a newly organized group involving seven universities (California, Chicago, Harvard, Indiana, Michigan, Ohio State, and Wisconsin), all having large observatories with active programs in astronomical research, has completed arrangements with the National Science Foundation to build and operate a new observatory for basic research. R. R. McMath of the McMath-Hulbert Observatory in Michigan is the President. The main office will be in Phoenix, Arizona. The site is not yet chosen, but one of three Arizona sites is the likely choice. The initial plans call for telescopes of 80 and 36 inches.

NEW ZEALAND PROGRAM FOR RADIOCARBON DATING—The New Zealand Department of Scientific and Industrial Research, in its studies on industrial effects, has found that the effect is the same in the atmosphere of the Southern Hemisphere as in the Northern Hemisphere. The exchange time for atmospheric circulation between the two hemispheres is less than twelve years, and the mean life of a carbon dioxide molecule, before being absorbed into the ocean, is less than seven years. They have substantiated the idea that H-bomb tests tend to enrich the atmosphere in C_{14} and that the C_{14} specific activity of the atmosphere was increased by four per cent in the interval from February, 1955, to October, 1956. The study of C_{14} activity of sea water from Makara has continued, and already an increase has been detected. Further measurements are contemplated to demonstrate this increase, and sea-water samples from varying depths have been collected from a station over the New Caledonian Trench in the expectation that the results will give base-line data on the age of the ocean before the H-bomb effect and offer scientists opportunity to estimate the size of the upper and lower reservoirs of the ocean.

RADIO ENGINEERS' CONFERENCE—The Southwestern Institute of Radio Engineers will hold a conference and an electronics show in San Antonio, Texas, April 10-12, 1958.

Personalia

KEITH E. ANDERSON, formerly Regional Drainage and Groundwater Engineer for the Bureau of Reclamation in the Pacific Northwest, has opened an office in Boise, Idaho, as consultant in engineering and geology, with specialization in groundwater, drainage, and irrigation problems.

JAMES L. DYSON, Head of the Department of Geology at Lafayette College, has received an award of $500 from the Thomas R. Jones Fund for the Reward of Superior Teaching at Lafayette College. This is the second time in two years that he has received the award.

MILTON GREENBERG, Director of the Geophysics Research Directorate, Air Force Cambridge Research Center, has been awarded the Medal for Exceptional Civilian Service by the Secretary of the Air Force. He was cited for "his unusual efforts as an organizer, manager, and leader" which "aided greatly in the development of an organization that has earned an outstanding reputation for scientific and technoloigcal achievement and has made important contributions to the research and development program of the U. S. Air Force."

LEONARD C. HALPENNY has announced the establishment of the Water Development Corporation in Tucson, Arizona, specializing in problems of groundwater hydrology and related fields.

PAUL K. KURODA has left his work as Associate Professor of Chemistry at the University of Arkansas and has taken up new duties with the Argonne National Laboratory as Associate Chemist.

WALTER D. LAMBERT, Chief of the Gravity and Astronomy Section of the U. S. Coast and Geodetic Survey, retired, and now Consultant in Geodesy at Ohio State University, was awarded an honorary degree of Doctor of Science recently by Ohio State University.

GORDON A. MACDONALD has left his work with the U. S. Geological Survey in Denver to accept an appointment as Professor in the new Institute of Geophysics at the University of Hawaii and the Department of Geology at the University. He took up his new duties in February, 1958. In connection with this work with the Institute of Geophysics, he expects to establish volcano research in cooperation with the Hawaiian Volcano Observatory of the U. S. Geological Survey.

ALFRED C. REDFIELD of Woods Hole Oceanographic Institution is a national Sigma Xi lecturer. His topic is "The Proportions of Things in the Sea."

FREDERICK D. ROSSINI, Head of the Department of Chemistry of the Carnegie Institute of Technology and Chairman of the Division of Chemistry and Chemical Technology of the National Research Council, was one of the principal speakers at the Indian Science Congress which opened on January 6, 1958, in Madras.

PAUL A. SIPLE has returned from a year at the South Pole, during which time he was scientific head of the United States base established there. He was recently awarded the American Geographical Society's David Livingstone Centenary Medal. He has also been named the recipient of the Army's Distinguished Service Award for his scientific leadership at the South Pole.

ATHELSTAN SPILHAUS, Dean of the Institute of Technology at the University of Minnesota, has resigned his membership on the Board of UNESCO, effective as soon as the U. S. Government has selected a replacement.

LORENZ G. STRAUB, Head of the Civil Engineering Department of the University of Minnesota and Director of the St. Anthony Falls Hydraulic Laboratory, has been given one of the research prizes of the American Society of Civil Engineering.

HAROLD C. UREY, Professor, Enrico Fermi Institute for Nuclear Studies, University of Chicago, and Nobel Prize winner in Chemistry in 1934, has been appointed Professor of Chemistry at Large at the University of California. His laboratory and headquarters will be at the La Jolla campus beginning in June, 1958.

WARREN WEAVER, Vice President of the Rockefeller Foundation for Natural and Medical Sciences, has been given the Public Welfare award of the National Academy of Sciences.

HANS F. WINTERKORN, Professor of Civil Engineering at Princeton University and specialist in the field of soil stabilization, has been awarded the Officer's Cross of the Federal Order of Merit, the highest civilian decoration of the German government.

CHARLES FRANKLIN BROOKS, Professor Emeritus of Meteorology at Harvard University and until his retirement in August, 1957, Director of the Blue Hill Meteorological Observatory of Harvard University, died January 8, 1958, at the age of 66. He was born in St. Paul, Minnesota, and took his baccalaureate degree at Harvard in 1911 and his doctorate from the same university in 1914. He founded the American Meteorological Society in 1919 and served faithfully as Secretary of that organization from the time of its founding until 1954. He had been a member of the American Geophysical Union since 1929. One of his many contributions to science appears in this issue of the *Transactions*, in collaboration with Mrs. Brooks. His devotion to science and his fellow man was an inspiration to all who knew him.

HENRY C. CORTES, Vice President and Director of Magnolia Petroleum Company, died in Honolulu December 6, 1957, while enroute with Mrs. Cortes to spend Christmas with his daughter and her family on Formosa. He was born in Houston, Texas, and pursued studies at the University of the South, and was recently awarded an honorary doctorate. He had planned to retire from his duties with Magnolia at the end of

1957. He began his professional career with the Vacuum Oil Company, where he continued serving as Director of Geophysics from 1928 to 1932 at which time there was a merger with the Magnolia Petroleum Company. He continued his duties as Director of Geophysics for the combined companies until 1946, when he was made Assistant Manager of the Exploration Division. He became a member of the Board of Directors in 1954 and in 1956 was made a Vice President of the company. He received wide recognition for his work in offshore oil exploration which involved fundamental and applied research. He had been a member of AGU since 1944.

Reginald Aldworth Daly, Sturgis-Hooper Professor Emeritus in Geology at Harvard University, died September 19, 1957, at the age of 86. He was born at Napanee, Ontario, took his baccalaureate degree from the University of Toronto in 1891, his master's degree from Harvard in 1893, and his doctorate in 1896. He studied at the University of Heidelberg and the Sorbonne. He was the recipient of a number of honorary doctorates and a member of the National Academy of Sciences. He was a recognized international authority on various geological subjects, especially those relating to structural geology. He was one of the original members of AGU, and in 1946 was designated as the Eighth Recipient of the William Bowie Medal.

Roy Waldemar Goranson, member of the staff of the University of California Radiation Laboratory, died December 25, 1957, at the age of 57. He was born at New Westminster, British Columbia, Canada, took his baccalaureate degree from the University of British Columbia in 1922, his master's degree from Harvard in 1923, and his doctorate also from Harvard in 1931. He began his career as a fellow in Optical Mineralogy from 1924 to 1926, and from 1926 to 1948 with the exception of the war years was with the Geophysical Laboratory of the Carnegie Institution of Washington. From 1948 to 1952, he was at the Los Alamos Scientific Laboratory. He took up his duties at the Radiation Laboratory in 1953. He had been a member of AGU since 1930, and had served as a member of various committees.

Bjørn Helland-Hansen, long one of the world's outstanding leaders in oceanography and Past President of the International Union of Geodesy and Geophysics, died in Norway, September 7, 1957, in his 80th year.

Elbridge Churchill Jacobs, Professor of Geology and Mineralogy at the University of Vermont, retired, died December 12, 1957, at the age of 84. He took his bachelor's degree from Massachusetts Institute of Technology in 1896 and his Master of Science degree from Columbia. He began his career as assistant in mineralogy at Massachusetts Institute of Technology and in 1899 took up duties as instructor in chemistry and mineralogy at the University of Vermont, where he continued until his retirement in 1944. During this interval, however, he was active in related work on flood-control investigations and served as State Geologist for Vermont from 1943 to 1947. He had been a member of AGU since 1934.

John Christian Jensen, Professor of Physics of Nebraska Wesleyan University, retired, died on his birthday, October 19, 1957, at the age of 77. He was born at Utica, Nebraska, took his baccalaureate degree from Nebraska Wesleyan in 1909, his M.A. from Nebraska in 1916, and his Ph.D. from Nebraska in 1939, studying also at the University of Iowa in 1916 and the University of Chicago in 1921. He began his professional career in school-teaching work in 1903. In 1907, as a student, he began teaching at Nebraska Wesleyan where he continued until his retirement in 1952. He served in many other capacities at the University, such as Dean of Men and as Coordinator of the Civil Aeronautics Administration. After his retirement in 1952, he was Visiting Professor at Cornell College in 1952 and 1953 and had been doing consulting work in physics since 1953. He became a member of AGU in 1930 and a Life Member in 1952.

Robert Talbot Knapp, Professor of Hydraulic Engineering at California Institute of Technology, died November 7, 1957, at the age of 58. He was born in Loveland, Colorado, took his baccalaureate degree from Massachusetts Institute of Technology in 1920 and his Doctor's degree from California Institute of Technology in 1929. He began his professional career as a designer for the Gay Engineering Corporation in 1920, but in 1922 he took up duties as instructor at the California Institute of Technology and, excepting for various war assignments, continued his work there until the time of his death. He served as consultant in various engineering work and in 1929 was chosen as a Freeman traveling fellow in hydraulics, devoting a year to study in Europe. Incidental to his work at California Institute of Technology, he undertook various assignments with respect to the Department of Agriculture and the designing of equipment for the Bureau of Reclamation. During war years he was with the Office of Scientific Research and Development. He had been a member of AGU since 1934.

Frederick Law Olmsted, noted Landscape Architect, whose skill was reflected in the development of Central Park in New York, the Mall, Rock Creek Park, and other areas in Washington, and the parks of many other cities, died in Malibu, California, December 26, 1957, at the age of 87. He was born on Staten Island, New York, and took his baccalaureate degree from Harvard University in 1894, receiving an honorary master's degree from Tufts in 1926. He began his work as Landscape Architect in 1895 as a member of Olmsted Brothers of Brookline, Massachusetts, and developed his work through this company up to within a short time before his death. He became a member of the American Geophysical Union in 1949.

Howard Edwin Tatel, Research Physicist of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, died November 15, 1957, at the age of 43. He was born in New York, and took his baccalaureate degree from Massachusetts Institute of Technology in 1935, his master's degree in 1936, and his doctorate from Stanford under a Rosenberg Science Fellowship in 1940. He did research work in physics at the University of Michigan, worked with the Carnegie Institution of Washington from 1941 to 1943, and with the Applied Physics Laboratory of Johns Hopkins University from 1943 to 1947. In 1947, he returned to the Carnegie Institution where he continued until the time of his death. Only a short time before his death, he had returned from a scientific expedition in Bolivia and the Highlands of the Andes on work connected with the International Geophysical Year. He had been a member of AGU since 1950.

Union, Section, and Committee Activities

Minutes of Executive Committee Meeting, American Geophysical Union October 25, 1957

The meeting was called to order at 10h 07m in the Conference Room of Assistant Secretary of the Interior Aandahl, Room 6622 Interior Building, Washington, D. C., by Vice President Lloyd V. Berkner in the absence of President Ewing, who was unable to attend because of illness.

Present—P. H. Abelson, L. H. Adams, L. T. Aldrich, W. W. Atwood, Jr., Lloyd V. Berkner, Walter H. Bucher, J. J. Capello, S. D. Cornell, Earl G. Droessler, Robert E. Gebhardt, Harry H. Hess, Albert J Hoskinson, B. F. Howell, Jr., H. R. Joesting, J. W. Joyce, W. C. Krumbein, H. E. Landsberg, John Lyman, Thomas Maddock, Jr., A. G. McNish, L. M. Murphy, Jerome Namias, James H. Nelson, Charles Pierce, John C. Reed, Roger Revelle, A. N. Sayre, J. F. Schairer, Waldo E. Smith, and C. A. Whitten.

Approval of minutes—The minutes of the Executive Committee meetings of April 28 and May 1, 1957, published in the August 1957 issue of the *Transactions* (pp. 599–609), were approved.

General Secretary's Report

The last report of the General Secretary is recorded in the minutes of the Executive Committee meeting of April 28, 1957 published in the August 1957 issue of the *Transactions* (pp. 599–602).

The officers of the Union met on July 25, 1957, some of the purposes of which were to work out new arrangements for an advertising representative (Howland and Howland of New York are now undertaking this work), establish new advertising rates, and discuss the possibilities of joining our *Transactions* with the *Journal of Geophysical Research*, and issuing the *Transactions* on a monthly basis. At that time the officers, recognizing that additional revenue would be necessary to maintain the *Transactions* at the present level of excellence, considered various means of increasing revenue. One suggestion was to make a per-page charge of $10 which would entitle the author to 100 reprints. Small numbers of additional reprints would be priced at a level somewhat higher than is now charged, and large numbers would be furnished at a price about equal to the present charges. In view of the wide variation in practice in different disciplines and different journals, this matter should deserve wide and open discussion among members of the various Sections so that their representatives will be prepared to present the pros and cons of this and alternative schemes.

Also, the group went over with Chairman Joyce of the Committee on International Participation and Director Atwood of the Office of International Relations of NAS-NRC the proposed new Statutes and By-Laws for the IUGG and made positive recommendations.

Chairman Gerson of the Committee on AGU Relations with IGY was present, and there was a brief discussion of the work of that Committee which will be reported on in detail later at this meeting.

The monograph series was also discussed, and it was concluded that to finance this series properly we must secure a revolving fund from a foundation or some other source. However, before such financing can be gained, we must have in mind some rather firm titles for further symposia or groups of papers suitable for the monograph series.

The striking of additional Bowie medals by the U. S. Mint in Philadelphia was approved.

Publications—The following issues of the *Transactions* have been printed and distributed since our last meeting:

April 1957: 141 numbered pages of text plus 90 numbered pages of Directory plus 37 unnumbered pages including 17 pages of paid advertising; edition of 6300

June 1957: 160 numbered pages of text plus 16 unnumbered pages including 9½ pages of paid advertising; edition of 6300

August 1957: 194 numbered pages of text plus 26 unnumbered pages including 18½ pages of paid advertising; edition of 7200

The August issue was released in a larger edition in order that copies might be given to the delegates of the Eleventh General Assembly of the International Union of Geodesy and Geophysics without charge.

The Executive Committee last spring approved in principle the idea that we should indicate our willingness to publish in our *Transactions* the new *IGY Bulletin* to be issued by the U. S. National Committee for IGY if this could be done without decreasing the number of text pages and without cost to AGU. Arrangements have since been worked out along these lines, and *IGY Bulletins* 1 and 2 were published in the August issue of the *Transactions* and *Bulletins* 3 and 4 will appear in the October issue. In working out arrangements for this, the format was modified somewhat from ours and a somewhat larger type font was used to make for easier reading. This material does not receive the same scrutiny by the Editorial and Publication Committee as other material submitted for publication in the *Transactions*. Closer scrutiny is not possible (1) because of the very tight time schedule on which our printer does this job, and (2) the fact that it is essentially an IGY news letter which the IGY Committee feels should be published. There are deviations also from our format standards other than the type font and size which are not deemed to be objectionable. Many of our members feel that this material is a valuable addition to the *Transactions*. It also provides a desirable opportunity of cooperating with the IGY Committee.

The October 1957 issue of the *Transactions* is about ready for distribution and possibly will be packed for the mails on Saturday, October 26. The printer again has been somewhat slow in making delivery, but in this particular case it gave Howland and Howland of New York a little more time to secure additional advertising. The October issue will contain 188 numbered pages of text plus 20 unnumbered pages, including 11½ pages of paid advertising, with an edition of 6200. We are hopeful that the number of pages of advertising will now begin to increase substantially. Starting with the August issue, the basic charge per page of advertising was established at $250 instead of $100. We are attempting to emphasize in our advertising prestige and good-will, or public relations, rather than just straight commercial advertising. Those of you who are in influential positions in your companies, or have cordial relations with companies that you feel should appropriately advertise in the *Transactions*, can be helpful in arranging for advertising or indicating to the office of AGU companies that might consider the prestige and good-will of advertising in the *Transactions* worth while. This aid is most urgently needed.

The Editorial and Publication Committee has met regularly at bimonthly intervals to consider the many problems of the *Transactions*, including its continual improvement.

We have recently received notice from the printer that our printing costs are going up about 20 per cent (about $5000 a year) starting January 1, 1958. Consequently, if we are to maintain the present high standards, it appears that it will be necessary to augment our income from publications.

The officers have discussed and, I believe, other groups are also considering the desirability of attempting to issue our *Transactions* on a monthly basis, perhaps starting in 1959. Negotiations toward combining the *Transactions* with the *Journal of Geophysical Research*, if appropriate financial arrangements can be made, seems to be a desirable objective.

Negotiations have been completed with the Johnson Reprint Corporation for reprinting the out-of-stock numbers of our *Transactions* and for the sale of our stock of *Transactions* prior to 1954. The stock of *Transactions* prior to 1954 has been turned over to Walter J. Johnson, Inc., and payment therefor is expected in the near future.

Plans for continuing the Geophysical Monograph Series are still in abeyance. We must find ways and means for implementing this series so that appropriate documents may be printed. We are still seeking a fund of $50,000 to $100,000 to set up as working capital, and any suggestions to this end are invited.

We have received grants totaling $40,900 from the National Science Foundation to cover the Russian translation project for the year. This will involve the translation and publication of *Izvestiia* (Geophysics Series), the translation and publication of geophysical abstracts relating to material published in eastern Europe, Russia, and the mainland of China, and a review or survey of *Trudy* (of the Geophysical Institute) to see what particular material should be set up as special translation projects. So far, the Pergamon Press, with whom arrangements have been completed for the translation, publication, and sales work, has not produced any complete copies. It is expected that No. 2 of *Izvestiia* for 1957 will be forthcoming soon, with No. 1 to follow shortly thereafter. An Editorial Board, consisting of Perry Byerly (Chairman), Walter B. Langbein, John Lyman, F. W. Reichelderfer, A. E. Scheidegger, Waldo E. Smith, and Victor Vacquier, has been established to advise on this project. A questionnaire was mailed out to about a thousand addresses in early September with the main purpose of establishing a list of about 500 who would be able to help us in shaping this project in the months and years ahead.

Membership—Earl G. Droessler has taken over actively as Chairman of the Committee on Membership. He has established sections responsible for certain phases of the work. The following section chairmen have been designated: Elliott B. Roberts, Chairman for Government Memberships; B. F. Howell, Jr., Chairman for Academic and University Memberships; Nelson C. Steenland, Chairman for Industrial and Commercial Memberships (both individual and corporation); Paul A. Smith, Chairman for Admissions; and Willis B. Foster for Brochures and Publicity. So far, activity has been greatest among the government group. However plans for implementing other phases of the membership drive have shown much progress and should soon be in full swing. New brochures have been issued to facilitate the work.

Membership data are:

Membership as of April 25, 1957	4980	
Reactivated	1	
New members, April 25 to October 16, 1957, including 14 applications now being processed toward membership	229	5210
Resigned	32	
Inactive	3	
Dropped	136	
Deceased (reported since April 25, 1957)	18	189
		5021

Dues unpaid—As of October 16, 1957, the following dues were unpaid:

Owe for 1957	285
Owe for part of 1957	13
Owe for 1956 and 1957	172
Owe for part of 1956 and all of 1957	12

Deaths—The following 18 deaths have been reported to the Union office since our last meeting: Robert W. Kellogg, April 13, 1956; Paul L. Heslop, November 7, 1956; Paul S. Kraus, November 10, 1956; William H. Twenhofel, January 7, 1957; Hans Kramer, February 16, 1957; O. J. Backus, February 24, 1957; Juan Jagsich, April 3, 1957; John W. Pritchett, April 19, 1957; C. E. Deppermann, May 8, 1957; George W. Trauger, June 1, 1957; John C. Rabbitt, June 10, 1957; Herbert R. Morgan, June 11, 1957; Arthur A. Lane, June 17, 1957; Eugene F. Bangs, June 22, 1957; Irving Langmuir, August 16, 1957; C.-G. Rossby, August 19, 1957; H. U. Sverdrup, August 20, 1957; Ladislao Adler, September 4, 1957.

Finances—Below is a brief statement of our assets as of October 1, 1957, with comparisons for the last two years.

	Oct. 1, 1957	Oct. 1, 1956	Oct. 1, 1955
Cash balance	$17,728	$18,216	$14,152
Permanent Fund	14,055[a]	13,075[a]	12,348[a]
Emergency Fund	1,000	1,000	1,000
T. M. & E. Award Fund	1,288	1,268	985
Russian Translation Fund	40,067	......	......
	$74,138	$33,559	$28,485

[a] Does not include accumulated interest on $2368 of U. S. Savings Bonds.

After making adjustment for the payment for the August issue of the *Transactions*, we have about $4500 less than we had a year ago, and in that fiscal year we incurred a deficit of about $2000. The increase in the cost of printing between January 1 and July 1 will amount to about $2500. Therefore, we have cause for concern over our financial situation. We are hopeful that advertising and membership increases will improve this situation before the end of the current fiscal year, but, if not, prompt steps will need to be taken in 1958 to augment the Union's income.

The financial statement for the year ending June 30, 1957 has been completed and audited by the Audit Committee, and will be presented later in this meeting.

Office staff and jobs—At the present time there are four full-time staff members including a student from Antioch College who is with us as a part of her college work. The office staff includes James J. Capello, Ethel G. Sanders, Susan Davis (the student), and Waldo E. Smith, Executive Secretary. In addition, Glenda Quinn Olmstead, who has been a full-time member of our staff at various times in the past, is continuing with us about half time, Barry Modlin (a student at George Washington University) about a quarter time, and Marc Klaben (a high school student) after school in the afternoon.

Quarters—We continue to occupy five rooms in the building of the American Association for the Advancement of Science at 1515 Massachusetts Ave., N.W. These are proving very satisfactory for our present requirements.

International matters—The Eleventh General Assembly of the International Union of Geodesy and Geophysics was held in Toronto, September 3–14, 1957. About 1400 attended from some 50 countries, with about 500 in attendance from the United States. At that meeting the decision was made to hold the Twelfth General Assembly in Finland, July 25–August 8, 1960. J. Tuzo Wilson of Canada was elected President for the triennium now beginning, with V. V. Beloussov of USSR and W. A. Heiskanen of Finland as Vice Presidents. G. Laclavere was reelected General Secretary. Joseph Kaplan was elected President of the Association of Geomagnetism and Aeronomy and H. G. Wilm as President of the Association of Hydrology. C. A. Whitten was elected Vice President of the Association of Geodesy, Horace R. Byers as Vice President of the Association of Meteorology, and J. Frank Schairer as Vice President of the Association of Volcanology. Amendments were made to the Statutes and By-Laws. A report on the meeting will be given by President Ewing, who served as Chief Delegate, and more details will be presented by Chairman Joyce of the Committee on International Participation later at this meeting.

Meetings—The Pacific Northwest Regional Group will hold a meeting October 29–30, 1957, in Pullman, Washington, and the Executive Secretary will attend. It is felt that these activities should perhaps have greater support from the national organization, and upon the urging of members of the Regional Committees it was decided that one of the officers should attend each of these regional meetings.

The regional meeting of the Pacific Southwest Regional Group will be held in Pasadena, February 6–7, 1958. The General Secretary plans to arrange his schedule so as to attend that meeting.

Our annual meeting is set for May 5–7, 1958. We shall have a report from Chairman Abelson of the Committee on Meetings with regard to plans for this. Suggestions for symposia that have come into the office include one on aeronomy, perhaps along the lines of the one held in Toronto. Another has been suggested by the Special Committee on Cosmic-Terrestrial Relationships (E. H. Vestine, Chairman) and still another involving phases of geochemistry under the guidance of Abelson. We will leave in the hands of the Committee the development of appropriate plans.

It was anticipated that a meeting of AGU might be held in cooperation with the meeting of the American Association for the Advancement of Science between Christmas and New Year's Day in Indianapolis, and Edward M. Brooks of St. Louis was invited informally to explore this. AGU expects to cosponsor a symposium on "Weather and its relation to man" arranged by Section M (Engineering) of the AAAS. The American Meteorological Society will also be a cosponsor.

A Conference on Atmospheric Chemistry of the Compounds of Chlorine and Sulphur is to be held in Cincinnati, November 4–6, 1957, in cooperation with the U. S. Public Health Service. James P. Lodge, Jr., of that Service and Chairman of the Committee on Atmospheric Chemistry of our Section of Meteorology has been instrumental in arranging the meeting. The National Science Foundation has made a grant of $4000 to cover the cost of travel of foreign participants. No provision has been made as yet for the publication of the papers to be presented.

Statutes and By-Laws—The ballot has not yet been sent out concerning the changes in the Statutes and By-Laws approved by the Executive Committee at its meeting last spring because several meteorologists have objected to changing the name of the International Association to Geomagnetism and Aeronomy. The ballot was withheld until the close of the meeting in Toronto to see whether this decision might be reversed. Inasmuch as no action to reverse this decision was taken, it is planned that the ballot will be prepared and mailed soon. Also, some persons felt that the change in name of the Section of Terrestrial Magnetism and Electricity had not been formally approved by that Section of the AGU. At the meeting in 1956, nine voted to change the name to Geomagnetism and the Upper Atmosphere and six voted to change it to Geomagnetism and Aeronomy. The President of the Section, feeling that the vote was not decisive in view of the small number voting, recommended to the Executive Committee that the name be changed to Geomagnetism and Aeronomy to correspond to that of the International Association. This action has recently been challenged by a member active in the Section. However, since the Statutes and By-Laws of AGU do not require concurrence by the Section in the change, it is planned to proceed with this matter in the near future unless objection is raised in this meeting.

International Geophysical Year—In addition to the comments concerning the IGY activity noted above, a further report will be given by Chairman Gerson.

Education in Geophysics—A committee has now been appointed under the chairmanship of John E. Nafe and including H. R. Byers, C. T. Elvey, H. H. Hess, Patrick M. Hurley, Frank Press, Roger Revelle, Athelstan Spilhaus, C. W. Thornthwaite, James A. Van Allen, and H. G. Wilm. The committee perhaps has not yet had opportunity to organize, but later we will have a preliminary report from Nafe.

American Geological Institute—Henry R. Joesting completes his second term as one of our directors on the Board and cannot be reappointed. Appointment of two new directors is pending in the hands of President Ewing.

Miscellaneous—At the meeting in Toronto, where the Canadians made special arrangements for the entertainment of the wives of delegates, the question was raised by certain American women in attendance whether our annual meeting should provide for a Ladies' Committee to give special attention to entertainment of the ladies that may accompany their husbands to our meeting. The policy of AGU in the past with regard to all such matters has been negative inasmuch as ours is a purely scientific meeting extending a mere three days and the need for such entertainment has not arisen. Perhaps the Executive Committee will like to reconsider this matter at this time.

A number of years ago the Petroleum Research Corporation of Denver asked for permission to reproduce on micro-cards or micro-films papers published in the *Transactions* relative to the Rocky Mountain region. This was granted in 1953 covering the *Transactions* through 1953, with the arrangement to continue until June 30, 1955. They now ask extention of this to cover *Transactions* through 1957. It is recommended that this request be granted.

Plans seem to be developing slowly for the establishment of an Institute of Geophysics at the University of Hawaii. The initial sum proposed for this is now two and one-half million dollars instead of one million dollars originally suggested. This is a much more realistic figure.

The U. S. National Commission for UNESCO is holding a conference in San Francisco, November 6–9, 1957, and has asked us to designate representatives. We have requested three members (Robert C. Bundgaard, J. W. Johnson, and N. Allen Riley) in the San Francisco area to represent the AGU.

The Second International Conference on Peaceful Uses of Atomic Energy will be held in Geneva, September 1–13, 1958. The U. S. Atomic Energy Commission has invited AGU to submit names of authors, titles, and abstracts. If approved, they would be submitted to the Secretary-General of the United Nations.

A. NELSON SAYRE,
General Secretary

Action on recommendations in the General Secretary's report—There was discussion of the Russian translation project, it being noted by Harry Hess that there is a new project afoot in England to prepare international abstracts to cover the entire field of geophysics. It was agreed that we should take steps to see that this is correlated with our own endeavors. It was also agreed that payment to Pergamon Press for work on the Russian translation project should be on the basis of proof of performance. It was noted that about 150 answers to our questionnaire about the translation project had been received, most of these indicating their willingness to cooperate in giving us reactions to this effort as the project proceeds, in return for which they are to receive a copy of the abstract journal as it is issued. It was planned to build this list to about 500 addresses.

It was agreed that C. A. Oficina Technica de Obras Maritimas of Venezuela was a proper candidate for corporation membership, the question having been raised because of the fact that they are outside of the United States.

It was noted that President Ewing has designated Walter M. Bucher and James R. Balsley, Jr. to serve as our representatives on the Board of Directors of the American Geological Institute.

It was noted by Harry Hess that the bill for the establishment of an Institute of Geophysics at the University of Hawaii has not yet been acted upon by Congress.

Henry R. Joesting noted that the International Geological Congress has established an International Geological Abstracting Service for the abstracting of foreign publications and that Earl Ingerson has been designated as the United States representative on a committee to look into the possibility of securing National Science Foundation aid in this.

Reports of Standing Committees

Audit—Chairman A. G. McNish presented the report of the Committee covering the fiscal year ending June 30, 1957, which was accepted (see Appendix 1). It was noted that, in accordance with Executive Committee instructions, excess funds in our checking account have been transferred to an interest-bearing savings account in the Riggs National Bank. This savings account is currently $40,000. The Executive Committee agreed that this had been appropriately deposited.

International Participation—Chairman J. W. Joyce commented with respect to the Eleventh General Assembly in Toronto, outlining the various problems presented there including the revision of the Statutes and By-Laws. Because of the statutory requirements relative to these changes, they were necessarily based upon the draft circulated by the General Secretary of IUGG in the spring of 1957 and could not incorporate some of the principles that were presented in our own later draft which were looked upon as involving changes that did not meet statutory requirements with respect to time. The changes involved an enlarged Bureau of IUGG consisting of the President, two Vice Presidents, General Secretary, and three members at large (instead of the President and General Secretary as at present). Membership categories were revised, which will result in an increase in U. S. dues from £1500 per year to £3000. The General Assembly set up a committee for the further consideration of changes in the Statutes and By-Laws, and it is anticipated that there will be further changes in 1960. The new changes have the effect of improving continuity in the actions of IUGG, noting that the new Bureau is to meet in Paris on December 2–7, 1957, with plans to meet at least once a year in the interim until the next General Assembly in 1960.

There is the expectation that the agenda for the next General Assembly will be circulated to the various National Committees well in advance of the meeting in Finland in order to avoid the state of confusion that currently occurs in early meetings of the Council and the Executive Committee.

With regard to the representation of Germany and the Republic of China, it was urged that the scientists of these two countries attempt to get together to work out common representation in the IUGG. This seems immediately possible in the case of Germany. With respect to Cuba, a committee is to be appointed to determine what group in Cuba may most appropriately be representative of geophysics in the IUGG.

Representatives of the Sections to each of the Associations made brief reports relative to the Toronto meeting (these in general largely reviewed details which have already been covered in the report on the meeting published in the December 1957 issue of the *Transactions*, pp. 984–987).

Charles A. Whitten noted that the complete reports for the Association of Geodesy will appear in *Bulletin Geodesique* and that plans have been made to hold five international symposia during the next three years, including one in the United States on electronic surveying to be held in March 1959.

In Meteorology, Jerome Namias noted that the Association of Meteorology has decided to publish only the abstracts of the papers presented, recognizing that there are now a great many outlets for meteorological papers. He also stated that there was lively discussion concerning the use of the word "Aeronomy" by the Association of Geomagnetism and Aeronomy.

With regard to the Association of Geomagnetism and Aeronomy, J. Hugh Nelson noted that the sessions were excellent, especially the symposium on aeronomy, and that the Association took no steps to make further change in its name.

A. Nelson Sayre noted that the meetings of the Association of Hydrology were well attended, especially those relating to subterranean waters, and that there is great variability in the quality of the papers. Thomas Maddock noted that there was discussion of the tendency for interest in Association activities to drop off in the intervals between meetings and that to overcome this two symposia have been arranged for the interim, one relating to snow and ice and another to forests and water.

In the Association of Oçeanography, John Lyman noted that many of the American papers were excellent and that the isotope tracing technique is being looked upon as increasingly valuable in tracing ocean waters. He reported that the French are doing much on the optics of sea water. He urged that the matter of representation at all sessions in subsequent meetings should be carefully worked out. It was also noted that steps need to be taken to clarify certain difficulties in connection with the work of the Association of Oceanography. The Executive Secretary was directed to proceed to Seattle in connection with his trip to the regional meeting at Pullman to consult with Richard H. Fleming on this matter if it cannot be resolved otherwise.

In the Association of Seismology and the Physics of the Earth's Interior, Leonard M. Murphy noted that the group in geochemistry was seeking an outlet either through Volcanology or this Association, but was not sure how things would work out. He also noted that there were many high-quality papers, including a number from the USSR, that participants in the Association's meetings from the USSR were very cooperative, and that in this Association the matter of the feasibility and cost of drilling a test hole through the Mohorovicic discontinuity got its impetus.

J. Frank Schairer noted that the Association of Volcanology had a very active meeting but that there were no programs prepared in advance. It was agreed by the Association to establish four sections to include active volcanoes, volcanophysics, physical chemistry of magmas, and paleovolcanology and plutonism, with geochronology included.

With regard to the meeting in Toronto, Chairman Berkner indicated that President Ewing had requested him to raise two questions based on the experience at that meeting, (1) regarding the composition of the U. S. National Committee and (2) the matter of national reports for the various Associations. In general, it was felt that there should be some measures taken to review papers originating in the United States before being presented, and that in one or two cases failure to do this resulted in rather embarrassing situations. It was recommended that the whole matter of U. S. participation should be reviewed by the Committee on International Participation based on this experience, especially as there is likely to be considerably more activity between the Assemblies, and to see to it that the activities are appropriately monitored in the Associations and to make sure that the papers presented are of a satisfactory quality. A specific report should be made on these points in May 1958.

The matter of national reports before the various Associations also requires consideration. In some instances very complete printed reports were available for the various Associations. This requires long advance planning and, of course, involves also the principles in this connection desired by the Associations Proper reports would be quite voluminous and involve a good deal of work. It was thought that the reports should essentially be summaries of research, noting that the Canadians now put out a volume which summarizes their research for the year and that this plan might be followed.

It was noted that certain changes in the Statutes and

By-Laws were effected at the time of the meeting in Toronto and a continuing committee will work on this matter with the expectation that there will be further modification in 1960.

A meeting of the new Bureau of the IUGG is to be held in Paris in December 1957. It is expected that there will be a discussion of the new IUGG Chronicle, plans for the publication of symposia, and other material in a continuing professional journal in international geophysics. A geophysical bibliography will presumably also be discussed. The sentiment was strongly against IUGG undertaking the publication of a scientific journal. The abstracting problem, it was felt, had best be worked out in a commercial enterprise, but there is need for such a worldwide journal which might well dovetail into the work in which AGU is now engaged under a National Science Foundation grant. In connection with the organization and publication of symposia, the Chairman noted that: (1) Symposia must be carefully organized by sound leaders and the papers must be really representative of the progress in the field for subsequent publication with discussion as an integrated volume; (2) the symposium should have an editor appointed in advance to put them into proper form; (3) the International Union should make arrangements with a publisher to publish them on a commercial basis, not as an IUGG publication; (4) the symposia should be appropriately indexed; (5) they should be published promptly. The suggestion of the establishment of awards in geophysics to be undertaken by IUGG was not encouraged. It was felt that the Bureau, at its meeting in December, should look thoroughly into the financial situation of IUGG.

The Executive Committee recessed for lunch at 12h 45m, with a second session called to order at 13h 45m.

Editorial and Publication—Chairman Sayre noted that the Committee had met every two months, that the backlog is building up again, and that there has been some criticism that the contents of the *Transactions* are too heavy on the hydrologic side as compared with other phases of geophysics, perhaps because of the fact that in the broad sense hydrologic papers find their chief outlet in the *Transactions*.

There was discussion of the thought that the *Transactions* and the *Journal of Geophysical Research* might be joined and that this might become a monthly journal representing the circulation of both publications with a scientific editor and an editorial board of which only the scientific editor would receive compensation. This should be a balanced journal and provide a rapid place for persons to get first-rate articles into prompt publication. The journal should also include one review article each month; reprints of these can then be assembled under a single cover as a monograph if this seemed desirable. It was suggested that the modified journal be called the *Journal of Geophysical Research*, with a note at the bottom "Combined with the *Transactions* of the American Geophysical Union." It was noted that the flow of hydrologic papers is not likely to decrease but rather increase because of the increasing demands on our water resources. It was agreed that the President should appoint a committee to go into this matter thoroughly including financial and other arrangements, recognizing that it would probably take some outside support during a transition period and also involve an increase in dues.

The Executive Committee approved granting permission to the Petroleum Research Corporation of Denver to reproduce on micro-cards or micro-films the papers published in the *Transactions* relative to the Rocky Mountain region as an extension to the arrangement made earlier.

Nominations—Chairman L. H. Adams offered no formal report, but it was noted that all Sections should be alerted to activate their Nominating Committees in order that these may function during the winter and spring and shortly after the annual meeting in May 1958 be prepared to offer their formal slates of nominees in accordance with our regular nominating procedures.

Statutes and By-Laws—In the absence of Chairman K. Hilding Beij, it was noted that certain changes in By-Laws were approved at the Executive Committee meeting on April 28, 1957 [see p. 608 of the August 1957 *Transactions*]. Thus changes in By-Laws having now been published the required period of time are out for final action. The Executive Committee confirmed its action of last spring subject to the approval by the membership and the National Research Council of the appertaining Statutes. It was noted that certain changes in the Statutes are pending and that a ballot would be sent out soon. These are likewise set forth in the August 1957 issue of the *Transactions*, page 608.

Meetings—Chairman P. H. Abelson noted that the programs are set up by the Sections and that, since primarily only three Sections are involved in the IGY activity, those Sections might be encouraged to develop a symposium for the Annual Meeting next spring. It was noted that Chairman Vestine of the Special Committee on Cosmic-Terrestrial Relationships has talked about a symposium in this field and that Joseph Kaplan, the new President of the International Association of Geomagnetism and Aeronomy, had arranged a symposium on aeronomy at the meeting in Toronto which was outstanding and that there might be a further development of this. Chairman Abelson plans to get into touch with the various Section Chairmen to work out specific programs. The question was raised by the Executive Secretary whether it is felt we should alter in any way the general character of our meetings and whether we are putting too much emphasis on the division of geophysics into sections rather than on its integration. It was expressed by Chairman Berkner that perhaps our meetings in Washington should develop themselves more to general symposia, with the development of particular phases at national meetings in various locations outside of Washington. It was suggested that the Chairman of the Committee on Meetings feel out the membership on this matter and that possibly steps be taken to rotate national meetings in various locations either on a voluntary or on an invitation basis. It was agreed that planning is necessary.

Membership—Chairman Earl G. Droessler noted that the membership campaign is proceeding well. Appendix 2 is a formal report that he presented in summary, which was accepted. It was agreed that we should approve C. A. Oficina Tecnica de Obras Maritimas of Venezuela as a corporation member.

Budget—Chairman John C. Reed presented the interim report of the Committee as given in Appendix 3, which was accepted. It was noted that because of an increase in printing charges it may be necessary for us to draw on our limited reserve to the extent of as much as $5000 for the current fiscal year. The increase in publication costs is just about $5000, and an increase of $1.00 per member for dues would defray that. It was agreed, however, that we should not raise dues at this time but work instead on increasing the membership and securing more advertising. The matter of a per-page charge was discussed, and it was agreed that this matter should be studied by the new committee appointed to study the matter of combining the *Transactions* and the *Journal of Geophysical Research*, perhaps following the policy of the *Journal of Geophysical Research* and the *Physical Review*.

In connection with the Russian translation project, no overhead is now being charged, and it was agreed that we should enter into negotiations with the National Science Foundation to secure the customary 15 per cent to cover this project.

Reports of Special Committees

Award of William Bowie Medal—Chairman Walter H. Bucher reported that after a series of letter exchanges the Committee met in Toronto and selected J. Th. Thijsse as the twentieth recipient. In line with the policy adopted last spring, this is to be announced at this time and plans laid for an informal dinner and the publication of a four-page program. The folder as outlined by the Chairman will have an announcement of the bestowal on the first page, the second page will be a summary of the recipient's achievements, the third page will list the previous Bowie medalists, and the fourth page will contain the principles of bestowals of the Bowie Medal. The report was accepted.

The question was raised as to whether the William Bowie Medal can be awarded posthumously and, if so, that this might be a fitting honor to bestow upon C.-G. Rossby. There was general concurrence that posthumous awards should not be undertaken.

Advertising—Chairman N. C. Gerson was not present, but it was noted that on the basis of his report advertising rates were increased effective with the August issue. The basic rate is now $250 per page per issue.

Cosmic-Terrestrial Relationships—Chairman E. H. Vestine was not present, but note was made of the suggestion that he undertake the arrangement of a symposium in connection with the meeting next spring.

Tellers—It was noted that this Committee, under the chairmanship of J. H. Nelson, will soon have a task to perform in connection with the ballot on the changes in the Statutes.

Education in Geophysics—Harry H. Hess reported that he had met with Chairman John E. Nafe, who is setting up plans to proceed.

Reports of Sections

Volcanology, Geochemistry, and Petrology—The Paricutin films compiled by the late William F. Foshag are in need of editing and some general work. President J. Frank Schairer is looking into this problem and feels that AGU might go to the National Science Foundation to secure a small grant in order that these films may be put into proper shape and then perhaps placed in the film library of the Library of Congress.

National Research Council Reports

International Relations—Director Wallace W. Atwood, Jr. reported that there will be a General Assembly of ICSU in Washington, September 26–October 7, 1958, and that on November 23, 1957, there is to be a general meeting at which plans will be laid for this Assembly.

Earth Sciences—Chairman Harry H. Hess presented a summary of the report that appears as Appendix 4. This was accepted.

Affiliated Organizations

American Geological Institute—It was noted that James R. Balsley, Jr. and Walter H. Bucher have been appointed as AGU delegates on the Governing Board of the American Geological Institute.

New Business

Meeting of U. S. National Commission for UNESCO at San Francisco, November 6–9, 1957—AGU has been requested to send representatives to this meeting, and certain persons have been asked to serve. It was noted by Chairman Berkner that at the last meeting of ICSU a resolution was circulated pointing out that the Natural Sciences Division of UNESCO is getting less and less of the total of the UNESCO budget so that the situation is becoming critical. Inasmuch as ICSU obtains support on particular projects from UNESCO it is important that, if the situation offers, our representatives to the U. S. National Commission meeting should support this resolution. The Office of International Relations was requested to supply the necessary information.

International Geophysical Year—A report of a special committee appointed by Joseph Kaplan, Chairman of the U. S. National Committee for the IGY, with respect to what happens upon the close of the IGY, was presented. The report sets out that certain aspects of the IGY should be continued and that the Academy should take steps to see that this is given direction. This proposal was endorsed.

Adjournment—The meeting adjourned at 16h 45m.

A. Nelson Sayre, *General Secretary*
Waldo E. Smith, *Executive Secretary*

Appendix 1—Report of the Committee on Audit for the Fiscal Year Ending June 30, 1957

A. G. McNish, Chairman
E. B. Roberts R. H. Weightman

Your Committee on Audit has examined the books of the American Geophysical Union for the fiscal year ending June 30, 1957, and finds them in agreement with the statement of the Union's finances supplied by the Executive Secretary.

At the beginning of the current fiscal year the cash assets of the Union amounted to $41,895.32, including Series F bonds valued at purchase cost and deposits in the Permanent Fund. In addition, bills receivable were estimated at $7,183.18 and liabilities amounted to $3,564.89, leaving a surplus of $45,513.61. At the close of the present fiscal year the cash assets of the Union amounted to $80,832.25, including the abovementioned bonds and investments, with an estimate of bills receivable of $11,954.97 making the total assets of the Union $92,787.22. Liabilities including bills payable amounted to $43,799.76, leaving a surplus of $48,987.46. Approximately half of the cash assets and liabilities are due to the Russian Translation Project, for which funds have been received in the amount of $40,900 subject to expenses which will be incurred by the Union in prosecution of the project. Operating expenses of the Union during the past fiscal year exceeded income by $2,043.77, which is due in part to rental of quarters for the first year by the Union and in part to an increase in the cost of printing the *Transactions*.

Your Committee has examined the evidence of these assets which support the report of the Executive Secretary. Our report is not based upon a completely detailed audit of all financial transactions of the Union but on a careful examination of certain essential aspects to give the Committee complete confidence in the soundness of this report.

Your Committee wishes to compliment the office of the Executive Secretary for the excellent state in which the accounts of the Union are kept, all details being subject to documentary verification.

Operating Statement

(Fiscal year ending June 30, 1957)

Receipts			
National Research Council grant			$400.00
Income			
Dues, 1954 and earlier	$238.17		
1955	396.33		
1956	4,098.04		
1957	32,536.17		
1958 et seq	133.95		
Corporation Memberships	2,500.00		
Life Memberships	300.00	$40,202.66	
Sales of publications			
Transactions	$12,580.77		
Reprints	3,923.99		
Geophysical Monograph No. 1	7,733.85[a]		
Miscellaneous	43.60	24,282.21	64,484.87
Contributions to Permanent Fund			253.00[a]
Interest on Permanent Funds			419.95
Contribution to T. M. and E. Award Fund			250.00[a]
Interest on T. M. and E. Award Fund			37.52
Interest on deposit with Interstate Building Association			364.11[a]
Russian Translation Project			40,900.00[a]
Advertising receipts			5,667.46
American Geological Institute			19.22[a]
Sale of equipment (3 fans and 2 Dazor lamps)			97.00[a]
Miscellaneous			158.82
Total receipts			$113,051.95

Disbursements		
Publishing *Transactions*		
Printing	$23,138.07	
Preparing copy	7,757.65	
Honoraria to editors	1,312.50	
Mailing	1,177.86	
Advertising expense	2,317.85	$35,703.93
Reprints		2,033.34
General expenditures (office of the Union)		
Salaries (including Federal Social Security)	$18,320.43	
Stationery and supplies	1,341.01	
Postage and communications	1,384.48	
Office equipment	19.90	21,065.82
National Academy of Sciences pension plan		1,062.56
Expenses, Committee on Membership		40.00
Expenses, Committee on Advertising		17.25
Expenses, Section of Meteorology		15.00
Expenses, Section of Hydrology		17.00
Expenses, Meetings		
Annual Meeting	$1,423.24	
Regional Meetings	51.31	1,474.55
Investment: Deposited in Liberty Building Association, part of T. M. and E. Award Fund		250.00[a]
Investment: Deposited in Prudential Building Association, part of Permanent Fund		560.00[a,b]
Geophysical Monograph No. 1		6,218.04[a]
Rent		3,672.31
Legal services ($130) and audit costs ($300) for zoning appeal)		430.00[a]
Directory		2,119.36
Russian Translation Project		169.30[a]
Bowie Medal		14.00
President's fund		56.20[a]
Miscellaneous		6.36
Total disbursements		$74,925.02

[a] Non-budget items.

[b] This is actually a transfer of funds; the amount remains available to AGU.

Excess of disbursements over receipts

Disbursements (including transfer of $560 to Permanent Fund)	$74,925.02	
Adjustment for transfer	560.00	
Net disbursements		$74,365.02
Receipts (including special fund for Russian Translation Project)	$113,051.95	
Less balance in special fund for Russian Translation Project	40,730.70	
Receipts, regular AGU funds		72,321.25
Decrease in liquid funds, regular account		$2,043.77

Statement of assets and liabilities as of June 30, 1957 (see p. 143 of Feb. 1957 *Transactions* for statement of assets and liabilities as of June 30, 1956)

Assets		
Cash Reserve		
On deposit in Riggs National Bank	$54,625.02[a]	
On deposit in Interstate Building Association	9,864.11	$64,489.13
Permanent Fund		
Series F bonds purchased prior to July 1, 1948 (maturity value $3,200), at cost	$2,368.00	
On deposit in Northwestern Federal Savings and Loan Association as of July 1, 1957	9,770.15	
On deposit in Prudential Building Association as of July 1, 1957	1,916.87	14,055.02
Forwarded		$78,544.15

Brought forward			$78,544.15
Emergency Fund			
On deposit in Prudential Building Association as of July 1, 1957		1,000.00	
T. M. and E. Award Fund			
On deposit in Liberty Building Association as of July 1, 1957		1,288.10	2,288.10
			$80,832.25
Bills Receivable			
Dues			
1957 only	$3,992.00		
1956 and 1957	3,055.00	$7,047.00	
Publications			
Transactions (including back numbers)	$2,744.24		
Subscriptions	270.00		
Reprints	1,140.47		
Miscellaneous	28.27		
Monographs	387.83		
Advertising	337.16	4,907.97	11,954.97
			$92,787.22
Liabilities			
Bills Payable and advance payments			
Dues in advance (1958 et seq.)	$135.65		
Subscriptions in advance (1958 et seq.)	312.00		
June 1957 *Transactions*, balance due about	2,500.00		
Misc. (mainly credits a/c overpayments)	121.41	$3,069.06	
Russian Translation Project commitment		40,730.70	$43,799.76
Surplus (Capital Account)			48,987.46
			$92,787.22
[a] Riggs National Bank statement of June 30, 1957			$58,178.19
Less checks outstanding			3,553.17
			$54,625.02

Appendix 2—Membership Committee Report

The AGU membership campaign is proceeding with increasing momentum. We now have five outstanding section leaders appointed and all of them are working hard to bring in more new members.

The work of Elliot B. Roberts, Chairman of the Government Members Section, merits special note. He has received an enthusiastic response to his letter-writing campaign, he has been able to appoint AGU keymen in 60 different government agencies spread throughout the U.S. The keymen, through staff conferences, office circulars, and by personal contact are spreading information on the AGU and are recruiting new members. Recently we received a sheaf of 13 new membership proposals from one AGU keyman, A. M. Moore, Assistant District Engineer, Geological Survey, Portland, Oregon.

Another section leader whose outstanding work merits special mention is Willis B. Foster, Chairman of the Publicity Section. He has prepared two new very attractive and informative brochures which we printed in number. One brochure will be sent out to prospective student and regular members, and the other is for soliciting new corporation members.

Ben F. Howell, Jr. Chairman of the University Members Section, has launched his program, and with the opening of the school year he will extend it to cover all students and teachers in geophysics. Chairman Howell will ask a faculty member to sign up student members for the AGU at each of the schools offering courses in geophysics. In looking to the future, this is one of the most important elements in our membership drive, a large body of student members today will be regular members of tomorrow.

The Chairman of the Commercial and Industrial Members Section, Nelson Steenland, has only recently been able to devote his attention to the task of enlarging the list of AGU corporation members. He has a supply of the new brochures and other material, and expects to be in full operation soon.

Paul A. Smith has taken over chairmanship of the Membership Qualifications Section. He has begun to draft new criteria covering qualifications for the membership classes of the AGU. Any recommendations in his report will come before the Executive Committee at some future meeting.

EARL G. DROESSLER, *Chairman*

Appendix 3—Interim Report of the Committee on Buget for the Fiscal Year Ending June 30, 1958

J. C. Reed, Chairman
E. H. Bramhall L. O. Quam

This interim report comprises an analysis, as of October 1, 1957, of the American Geophysical Union budget for the fiscal year ending June 30, 1958 as presented to the Executive Committee last May and as approved by that Committee.

At the May meeting, the Executive Committee indicated that it would like the Budget Committee to expand its responsibility to include advice in financial matters to the Executive Committee. This has been discussed by the Budget Committee and none of its members feels qualified to give substantive advice in such matters. Some discussion was held as to the desirability of obtaining professional advice from a bank or other authority. The Budget Committee requests more direction from the Executive Committee in this matter. Incidentally, since the May meeting, a savings account in the amount of about $40,000 has been opened, from which the Union should derive a little more interest than was previously estimated. The amount of the savings account will vary from time to time as funds are needed or not needed for current operations. A substantial part of the funds used to open the savings account was from the National Science Foundation for the translation responsibility and did not appear in the budget approved last May.

In the budget report approved in May, the receipt of $3000 from the sale of excess copies of the *Transactions* was anticipated. The item was not included in the budget because it was not known whether the money would be received in the 1957 or in the 1958 fiscal year. The funds, in the amount of $2400, have now been received and can be entered in the receipts column for the 1958 fiscal year.

Estimated Receipts

Item	Original budget estimate	Actual, 7/1–10/1	Estimate, 10/1–6/30 (based on actual in past fiscal year	Present estimate
National Research Council grant	$400	..	$400	$400
Membership dues	43,300	$2,996	36,671	39,667
Sales and subscriptions	12,000	1,096	11,140	12,236
[Monograph receipts, not previously budgeted]	..	398	602	1,000
Reprints	4,000	1,310	3,168	4,478
Advertising	6,000	2,964	4,370	7,334
Interest[a]	820	..	1,422	1,422
Miscellaneous	500	15	143	158
(Sale of *Transactions*, not previously budgeted)	..	..	2,400	2,400
	$67,020	$8,779	$60,316	$69,095

[a] Because of interest expected from the new savings account, this item has been increased $600 over the figure that otherwise would be estimated at this time. This was based on an assumed average of a savings account of $20,000 earning interest at 3 percent.

Estimated Expenditures

Item	Original budget estimate	Actual, 7/1–10/1	Estimate, 10-1–6/30 (based on actual in past fiscal year)	Present estimate
Transactions				
Preparation of copy	$7,900	$1,807	$6,133	$7,940
Printing[a]	24,000	8,961	18,778	27,739
Mailing	1,200	307	969	1,276
Editors	1,350	. . .	1,313	1,313
Advertising costs	2,500	59	1,717	1,776
Reprints	2,200	410	1,778	2,188
General Office expenses				
Rent	3,720	932	2,877	3,809
Salaries & social sec.[b]	17,000	4,758	14,177	18,935
Retirement contribution	1,050	266	797	1,063
Stationery and supplies	1,500	78	1,013	1,091
Postage and comm.	1,500	394	1,207	1,601
Equipment	500	19	20	39
Annual meeting	1,000	25	1,423	1,448
Regional meetings	100	. . .	29	29
Section expenses	100	. . .	11	11
Committee expenses	100	9	57	66
Travel	1,000	. . .	1,000	1,000
Directory reserve	1,000	. . .	1,000	1,000
	$67,720	$18,025	$54,299	$72,324

[a] Increase due to increased rate for printing.

[b] Increase due to some extra help used during summer and to fact that Union has been carrying some salary time expected to be carried by National Science Foundation funds for translations.

There follows a comparison of receipts and expenditures as estimated in the budget approved in May with the same items as estimated now.

From the above, it will be seen that receipts may amount to $2,075 more than earlier estimated and expenses may be $4,604 greater. As the earlier estimate indicated a deficit for the year of $700, the present estimate indicates a deficit of $3,229.

The committee greatly appreciates the assistance of the Executive Secretary in supplying the required data and in advising the committee.

Appendix 4—Report of the Union's Representative to the NRC Division of Earth Sciences 1956–1957

Your representative attended all meetings of the Executive Committee of the Division of Earth Sciences during the year (Oct. 13, Dec. 8, 1956, and Feb. 2, Mar. 30, April 27, 1957), all meetings of the Governing Board of the NRC and the annual meeting of the Division.

The following items of general or specific interest to the Union are culled from the year's activities of NRC division of Earth Sciences.

(1) (Meteorology) The Committee on Climatology Advisory to the Weather Bureau continued to function efficiently.

(2) (Hydrology) The Committee on Radioactive Waste Disposal on Land Advisory to AEC completed a report covering two years of its operation. This will be distributed by NRC before the end of November.

(3) (Oceanography) A conference to explore the needs for research in the field of oceanography was held on Feb. 19, 1957 in Washington. An outgrowth of the conference was the naming by President Bronk of Harrison Brown as chairman of a Committee on Oceanography. The field of interest of this committee will be somewhat broader than that of our Section of Oceanography inasmuch as it will include biological problems and conservation. Your representative urged the appointment of such a committee inasmuch as several of the most interesting fields of research in this area had suffered from lack of government liaison since the demise of the RDB panel on Oceanography.

(4) (Volcanology) A Conference on Basalts was organized for the day of the annual meeting of the Earth Science Division. The conference was most successful. Seventy-five people attended.

(5) (Volcanology) With the help of a small grant from NSF a conference on Tektites was held in Washington on June 17–18. About 30 scientists attended the meeting and considerable progress was made in defining the problems Tektites present and in indicating possible solutions.

(6) (General) The Proceedings of the Convocation at Woods Hole (June 22–24, 1954) were published as a volume of the Journal of Marine Research dated Dec. 31, 1955 but actually distributed in the summer of 1956. The volume contains many excellent papers relating to geophysics.

(7) (Meteorology, Oceanography) A Conference on Arctic Sea-Ice is to be held in February 1958.

(8) (Tectonophysics, Seismology) The Executive Committee of the Division sent a letter of congratulations to George Woollard on his achievement in getting seismographs into position on short notice to observe the recent underground nuclear explosion. The observations were made in Mexico at 18° and 20° from the explosion site.

Your representative would like to comment that much of the Division of Earth Sciences' activity has been in the field of geophysics in the last few years. It is most important for the Union to maintain close and cordial contact with NRC on the working level. By doing so the science of geophysics can be advanced and this should be our major objective.

H. H. Hess

Pacific Northwest Meeting Held in Pullman, Washington, October 28–30, 1957

The Fourth Pacific Northwest Regional meeting was held jointly with the Washington State College Hydraulics Conference at Pullman, Washington, on October 28–30, 1957. The joint sessions served to bring together the theoreticians and practical field men. An estimated 50 regional members of the Union attended the various scientific sessions, with actual attendance exceeding 100. Waldo E. Smith, Executive Secretary of the Union, was in attendance and spoke on certain aspects of the Union activities, including editorial policy and the status of the *Transactions*. A meeting of the Regional Committee was held on October 29. Wilbur D. Simons (409 Federal Building, Tacoma 2, Washington) was selected as Chairman for the year beginning July 1, 1958, and Vail Schermerhorn (320 Custom House, Portland, Oregon) as Secretary-Treasurer for the same period. It was decided to hold the 1958 meeting in Portland, Oregon. A business luncheon was held for the regional members on October 29, at which Milton S. Sachs addressed the group on the September meetings of the IUGG in Toronto.

Special Announcements

Thirty-Ninth Annual Meeting, Washington, D. C., May 5–8, 1958—Last-minute attention is called to the previous announcements regarding this meeting published in the *Transactions*, particularly that of October 1957, pages 797–798, relating especially to the program, and that of December 1957, page 989, bring-ng program matters up to date and giving information egarding hotel rooms.

The details of the program are rapidly being settled, nd in some Sections, notably Meteorology, the pro-ram is closed as noted in the December announcement. he programs for all other Sections close March 5. hree copies of titles and abstracts for these Sections hould be in at the latest by March 5. Keep abstracts rief and informative, giving concise results rather than n outline of the paper. Indicate projection equipment eeded and the amount of time desired (ordinarily 0–20 minutes are allowed).

Symposium on Snow and Glaciers—A symposium entitled "The Physics of Ice Movement" will be held by the International Association of Hydrology, IUGG, in Chamonix, France, September 16–24, 1958. Those interested in the symposium in the United States should get into touch with Ralph N. Wilson, Secretary of the Section of Hydrology, AGU, and those from other countries with their respective National Committees or with the Secretary of the International Association of Hydrology, L. J. Tison, 61, rue des Ronces, Gentbrugge, Belgium.

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NATIONAL ACADEMY OF SCIENCES

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IGY BULLETIN

A monthly survey by the U. S. National Committee for the International Geophysical Year. Established by and part of the National Academy of Sciences, the Committee is responsible for the U. S. International Geophysical Year program in which several hundred American scientists are participating and many public and private institutions are cooperating.

Oceanographic Expedition Downwind

Bulletin No. 2 described briefly some of the objectives of the IGY Deep Water oceanographic program and some pre-IGY work in the Atlantic Ocean. Many institutions in the United States and other countries are participating in this work.

Another major IGY cruise in the Pacific, expedition "Downwind," got under way on October 21, 1957, when two vessels, the *Horizon* and the *Spencer F. Baird*, left San Diego, California, for the central and south Pacific. These research vessels are operated by the Scripps Institution of Oceanography, La Jolla, California.

Earlier Cruises

Previous Scripps expeditions have covered much of the north Pacific through the waters south of Alaska, to Japan, and back. The central Pacific regions, from Hawaii to the Marshall Islands, southward to Fiji and Tonga, and back via Samoa, the Society Islands, the Tuamoto Archipelago and the Marquesas Islands, have also been visited. The "Midpac" cruise of 1950, during which the mid-Pacific submarine mountain range was explored, worked predominantly in the region from 15°N to 40°N. The "Capricorn" expedition of 1952–53, a joint operation by the *Horizon* and *Baird*, lasted five and one-half months and reached about 26°S.

During these previous expeditions, much work related to the present IGY oceanographic program was done. Extensive seismic refraction profiles were completed. In such operations one ship, the listening ship, lays to with hydrophones in the water while the other, the shooting ship, runs a line of seismic shots starting about 50 miles away from the listening ship. The shooting ship drops TNT charges ranging in size from several hundred pounds at the extreme limits of the line to one pound near the listening ship. This technique of exploration of the submarine crust has been used throughout most oceanic areas. Much effort has been devoted to study of the submarine crustal structure in areas of geologic interest, such as trenches, island arcs, fracture zones, isolated marine mountains, some of the great plateau areas, and undersea rises.

Other activities included in these expeditions are: taking cores of the bottom sediments; heat flow measurements through the sediments; surface current measurements with the geomagnetic electrokinetograph (GEK); deeper current observations with drogues; Nansen bottle casts for chemical studies and to obtain density data for use in calculating deep currents; underwater photography for study of marine life; drag and grab samples of the bottom in unsedimented areas; photographs of the bottom for geologic and biologic purposes; detailed bathymetry of trenches, sea mounts, and other features of topographic interest; observations of the magnetic field with towed magnetometers; and many kinds of marine biological work.

Downwind

The Downwind expedition will make most of the geophysical observations listed above as part of the IGY program to map the deep circulation of the oceans. The approximate track of the expedition is shown in Fig. 1. Oceanographic ships of Canada and the *Brown Bear* of the University of Washingto have covered areas north of the Scripp tracks as part of the plan to observe th currents in a long meridional profile. Ship of other countries, notably Australia, Ne Zealand, Japan, and Russia, have worke and are working in other areas of the Pacifi as part of the IGY plan to obtain extensiv coverage.

The leaders of the expedition are Henr W. Menard, Jr., and Robert L. Fishe

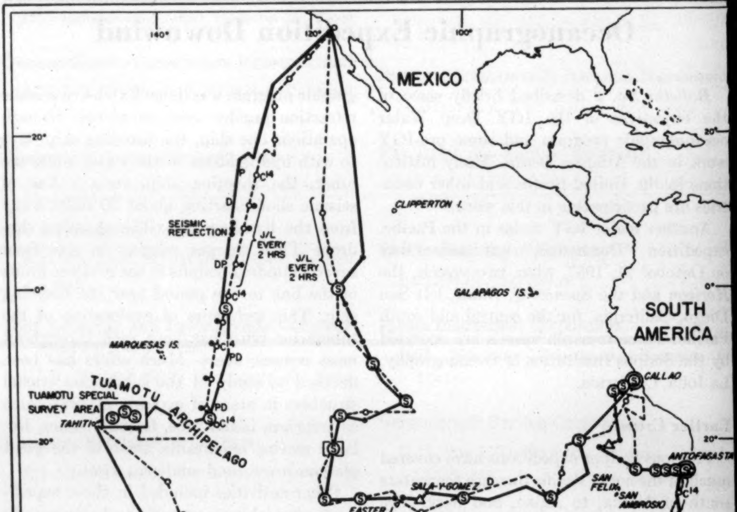
140°
120°
100°
MEXICO
20°
CLIPPERTON I.
SEISMIC REFLECTION
J/L EVERY 2 HRS
J/L EVERY 2 HRS
P
D
DP
C14
0°
GALAPAGOS IS.
SOUTH AMERICA
MARQUESAS IS.
PD
TUAMOTU SPECIAL SURVEY AREA
TAHITI
TUAMOTU ARCHIPELAGO
CALLAO
30°
ANTOFAGASTA
SALA-Y-GOMEZ
EASTER I.
SAN FELIX
SAN AMBROSIO
JUAN FERNANDEZ
VALPARAISO
MAS AFUERA
40°
DP
EAST PACIFIC RIDGE BUOY STATION
140°
120°
100°
80°

Fig. 1. *Track Chart for IGY Oceanographic Expedition* Downwind, *October 1957–February 1958. Symbols: circled* S*—seismic refraction station, including piston core and heat flow measurement; double-circled* S*—seismic refraction station, including piston core; triangle—heat flow measurement, including core; black dot—gravity core; small circle—hydrographic cast;* C^{14}*—radiocarbon sample;* D*—dredge haul;* P*—bottom photography.*

f the Scripps Institution. The scientific arty includes geologists, marine biologists, eismologists, chemists, oceanographers, and hree physicians. J. N. Nanda, Chief cientist of the Navy of the Republic of ndia, two Argentine, two Chilean, and two eruvian scientists are expected to particiate in the Valparaiso-to-Callao leg of the ruise.

bservational Program

During the Downwind expedition about 0 hydrographic casts will be made using ansen bottles and reversing thermometers; pecial samples will be taken for analysis of adioactive isotopes. Seven groups of bottom hotographs will be taken using an undervater camera developed by the U. S. Navy lectronics Laboratory.

A special probe developed at Scripps will e used at about 33 locations to measure eat flow through the oceanic sediments (only a small number of such measurements re now available). Heat flow data are useful n studies of crustal thickness and can also e applied to the study of the deep currents. During the Capricorn expedition, in 1953, he heat flow on the Albatross Plateau was nexpectedly high. This single measurement vill be checked by revisiting the general area. f heat flow for oceanic rises proves to be igher than for basins or trenches, it would end weight to suggestions that convection urrents in the earth's interior might be esponsible for tectonic effects at the crust.

These heat flow measurements are only part of the program of exploration of the marine crust. The cruise will establish the submarine topography of a profile along the 130°W meridian from the latitude of San Diego to about 50°S. About 15 dredge hauls will be made to collect samples as part of a study of the mineral resources of the sea floor, and almost 100 sediment cores are planned. Considerable attention will be devoted to a study of a most unusual topographic feature, the Tuamotu Archipelago. This group of atolls rises about one mile above the broad submarine ridges on which they stand. The ridges themselves are about a mile and a half higher than the deep sea floor. Twenty-five seismic profiles are planned, with emphasis in this and other areas of special geologic interest, such as the Easter Island Rise and the narrow, deep Andean Trench just off the coast of Chile and Peru. The relief from the bottom of this trench to the top of the adjacent Andes is the greatest in the world.

Progress

H. W. Menard has summarized the work accomplished in the first two weeks of the expedition in a radio message to Scripps. He reported the following: nine deep hydrographic casts made; twenty-four sediment cores taken; three dredge hauls made; twenty-six seismic reflection stations and two seismic refraction stations occupied, including one using a small boat for shooting; 162 bathythermograph observations made; four bottom photographs made; and twenty seamounts discovered, six of which have been surveyed in detail. The program for assay of CO_2 in the air and in sea water has been essentially continuous.

Menard describes some interesting results of these early observations. The four bottom photographs, at depths between 13,200 and 14,400 ft, are the deepest yet obtained in the Pacific. They all show evidences of biological activity, such as trails, mounds, holes, or a pavement of manganese nodules, depending on sediment type. Seismic reflection shots show sediments 984 ft thick at 20°N, thickening to 1640 ft at the equator. A seismic refraction run at the equator revealed normal sound velocity in the sediments and deeper layers. A piston sediment core contained 33 ft of recent calcareous ooze, but the heat conductivity measurement was surprisingly low—0.4 microcal/cm^2/sec. The daily averages of atmospheric CO_2 have ranged from 312 to 310 ppm.

Brief stops for refueling or local scientific investigation are scheduled at Papeete, Tahiti; Easter Island; Valparaiso, Chile; and Callao, Peru. The expedition will last about four and one-half months and will cover almost 40,000 miles of track.

Expedition Vessels

As the La Jolla location does not permit berthing of seagoing vessels, the ships of the Scripps fleet are docked at the Navy Electronics Laboratory facility at Point Loma, contiguous to San Diego harbor.

The two vessels, *Horizon* and *Spencer F. Baird*, are converted 143-ft ocean-going tugs; they are steel-hulled, single-screw, diesel-electric vessels, with displacement of 934 tons and draft of 16′5″ when loaded. The *Horizon* was acquired by Scripps in 1947, the *Baird* in 1951. The two ships have identical hulls but differing superstructures, and have been converted with somewhat different design.

The laboratory space on each ship is about 600 square feet. Each carries a crew of 17 and accommodates up to 15 in its scientific party.

For both ships, two twelve-cylinder Diesel engines driving separate direct-current generators and exciters supply power for two electric motors geared to a single shaft. The normal cruising speed is 11 knots with a range of about 10,000 miles. Food and water storage capacity allows about 45–50 days at sea between ports of call.

The after-decks or fantails of both ships are quite roomy; most equipment is lowered over the side from platforms either at the stern or at the side of the fantail immediately abaft the maindeck laboratory. Large A-frames have been constructed at the stern of each ship to handle the heavy and sometimes very bulky instruments. The A-frame of the *Horizon* rises about 28 ft from the deck. The main 35-hp winch is capable of handling 20,000 ft of $\frac{1}{2}$-inch wire. Other winches include a hydrographic winch with 20,000 ft of $\frac{3}{16}$ wire, a bathythermograph winch, and a special winch for electric cables, such as those used for the GEK and Thermitow instruments. The *Horizon*, usually the seismic shooting ship, has space for magazine storage of about 24 tons of explosives.

The A-frame on the *Baird*, with a platform about 35 ft above the fantail, is designed to handle loads of 20 tons. Her heavy winch, one of the three largest oceanographic winches in use today, is of the winding-machine type with electro-hydraulic drive and about 100-hp capacity. It is mounted immediately abaft the main deck laboratory. In conjunction with a storage reel mounted on the deck below, the winch handles up to 40,000 ft of tapered steel cable varying from $\frac{3}{8}$ to $\frac{3}{4}$ inch in diameter, and a shorter auxiliary cable of $\frac{1}{2}$-inch diameter. Two bathythermograph winches and two power-driven gypsies complete the power equipment on the fantail. On the boat deck are mounted two hydrographic winches, with capacities of 20,000 and 30,000 ft of $\frac{3}{16}$-inch wire. The *Baird* also has magazine storage space for explosives, and, as it is the listening seismic ship, the laboratory is equipped with seismic amplifying and recording equipment. A darkroom has been fitted out for immediate development of records and film.

Both ships are equipped with sonar, radar, considerable communications apparatus, loran, and echo sounders of both conventional type and newer precision models. The *Baird* also carries radio facsimile equipment.

Polar Ice and Snow Studies

The following article is based primarily on material supplied by Henri Bader of the US Army Snow, Ice, and Permafrost Research Establishment.

The major portion of the IGY effort in the field of glaciology is directed toward the study of ice and snow in the polar regions, particularly their glaciers and ice sheets. These studies will give information not only on the behavior of ice and snow under polar conditions but will also yield data on climate.

Two thirds of the area of the Greenland ice sheet and practically all of the Antarctic ice sheet are permanently dry. All precipitation is in the form of snow. Summer melt is rare and usually affects a surface layer only a few centimeters thick. Thus every snowfall, including everything that falls with it, is separately and safely filed away for future reference under later snowfalls.

The first man literally to dig into the 'files' was Sorge of the Wegener Expedition. At Eismitte in the center of the Greenland ice cap in 1930–31, he dug a 15-meter pit, counted the annual snow layers, and determined their density. During the past few years the records of the snow layers in Greenland have been examined in more detail and at greater depths by means of methods and instruments developed mainly by the US Army Snow, Ice and Permafrost Research Establishment (SIPRE).

Sorge's researches gave rise to a qualitative statement of the relationship of snow density, time, and climate. Sorge's Law is: At any given location in the dry snow region of a glacier, the density of the snow as a function of depth does not change with time unless the climate changes. SIPRE has given mathematical form to Sorge's Law and is expanding it to include the effects of changes in rate of precipitation and in temperature.

Snow is a poor conductor of heat; therefore, the amplitude of temperature variations in snow diminishes rapidly with depth. In Greenland the temperature at ten meters depth is almost constant and is within one degree of the mean annual air temperature. Thus, measuring the snow temperature at this depth gives important climatic data without the necessity of long-term meteorological observations.

By digging a pit, counting annual layers, and measuring snow density as a function of depth below the surface, the amount of annual precipitation for many years can also be determined. The usual procedure involves digging a pit several meters deep, measuring temperature and noting stratigraphy in the pit wall, and taking closely-spaced samples with standard ½ liter tubes for density measurements. For samples from greater depths, a hole is sunk from the bottom of the pit with a hand-operated core drill.

The identification of annual layers can be difficult unless there are thin ice crusts or other features to aid in distinguishing summer from winter layers. In Greenland it is possible to count annual layers almost without error, but in the Antarctic, there is much less precipitation and summers are much colder; therefore, the layers are thinner and not always characterized by ice crusts resulting from summer melt. It may be impossible to identify summer layers at high altitudes. A method of distinguishing between winter and summer layers by reason of the differing ratios of oxygen isotopes 16 and 18 in the snow has been developed by Samuel Epstein of the California Institute of Technology, but this method requires extensive laboratory work.

The tritium content of the snow can be used to estimate its age but only for snow which fell prior to 1954. Since then, hydrogen bomb tests have upset the natural tritium balance. Analysis for other radioactive contaminations in precisely dated snow layers in Greenland and in Antarctica will yield data on general atmospheric circulation since the first fission bombs were exploded in 1945. It should also be possible to follow the degree of atmospheric contamination resulting from industrial activity by analyses of snows down to the layers which fell in preindustrial times.

Natural substances which fall with the snow and are buried beneath succeeding layers—such as volcanic ash, meteorites, spores, and bacteria—are extremely well preserved. Ash from the 1912 eruption of the Alaskan volcano Katmai was easily identified in a snow layer at a depth of 32 meters below the 1954 snow surface at a point 200 miles east of Thule, Greenland. It is doubtful that this 1912 deposit, which is almost certainly continuous over the whole of Greenland, will be found in the Antarctic, but the ash of the 1883 Krakatoa eruption may prove to be identifiable in both hemispheres.

The deepest penetration into the past during the IGY is planned for the US deep drilling program which has been entrusted to SIPRE. In preparation, SIPRE, in 1956, drilled to 300 meters at its experimental station on the Greenland ice sheet. Core recovery was very incomplete, the primary objective being the development of drilling techniques. A modified Failing "1500" drill rig and especially designed core barrels are used for this work. Ice cuttings are removed by compressed air which has been cooled so as to prevent melting of the core or the wall of the hole.

In the summer of 1957 SIPRE drilled a still deeper hole at the same Greenland site, reaching a depth of 411 meters. Almost all cores were recovered to a depth of 300 meters but beyond that depth only two cores were brought to the surface intact, one from approximately 360 meters depth and one from 400 meters.

Core recovery from such depths is difficult because, as the snow is compressed under the load of overlying layers, its permeability decreases. At a density of approximately 0.83 the ice becomes impermeable, and with further densification the air in the enclosed bubbles is compressed. When the pressure of the overlying snow reaches 20 kg/cm^2 at a depth of 230 meters, the bubble pressure is 14 kg/cm^2, equal to the tensile strength of ice. Drilling releases the confining pressure, causing both the core and the ice forming the wall of the hole to crack. Cracking becomes worse with increasing depth.

The cores from the Greenland drilling have not yet been analyzed completely but annual layers of snow have been identified to the year 1700, ±10 years, and the age of the deepest core is estimated to be approximately 800 years. In Northeastern Greenland and in Antarctica, where the annual accumulation is much smaller, depths of 300 meters will include 2000 years of frozen history.

Other glacial pit studies and deep core drilling for the IGY program are already underway in the Arctic and Antarctic. Glacial pits have been dug at all the major US stations in the Antarctic. The deepest to date is the pit at the Wilkes Station which was sunk to a depth of 35.25 meters with a drill hole at the bottom of the pit extending another 27 meters.

Part of the equipment required for deep core drilling was delivered to Byrd Station by tractor train on October 24, 1957. The remainder will be delivered by air in the near future. Drilling will start as soon as the equipment is ready.

Other stratigraphic studies will be made by the European International Glaciological Expedition to Greenland, the Canadian Expedition to Northern Ellesmere Island, the US party at the McCall Glacier in the Brooks Range in Alaska, and by other nations at Antarctic stations.

Rocket Flare Patrol Program

Valuable data on solar X-rays during solar flares were obtained during July and August using rockets launched from San Nicolas Island, within the US Navy Pt. Mugu Range, sixty miles off the California coast. The rocket launchings were part of the DAN Rocket Flare Patrol Program, which is designed to determine the radiation source of the radio fadeouts caused by flares on the disk of the sun.

This IGY rocket program was conducted by the Electron Optics Branch of the Naval Research Laboratory (NRL) under the supervision of Herbert Friedman, and with the assistance of T. A. Chubb, J. E. Kuperrian, Jr., R. W. Kreplin, and J. C. Lindsay.

Flare-Upper Atmosphere Relationships

X-rays and Lyman-alpha radiation are two possible sources of the increased ionization responsible for radio fadeout conditions.

X-ray emission from a quiet sun arises in the million-degree coronal gas and consists of recombination continua and line emissions from all the atoms of the coronal atmosphere in their various states of ionization. In an ionization equilibrium at one million degrees Kelvin, the M shells of all atoms are stripped, corresponding to ionization potentials of several hundred electron volts (ev), or wavelengths of 20–100 Å. (The innermost shell of an atom, containing two electrons when filled, is designated the "K shell"; the "L shell," with 8 electrons when filled, lies next to the K shell; and the "M shell," containing at most 18 electrons, is next to the L shell). If the temperature of a local coronal condensation is increased to five million degrees Kelvin, the K shells of the lighter elements up to oxygen may be ionized, corresponding to ionization energies of the order of 1500 ev, or wavelength of about 8 Å. A much greater rise in temperature would be necessary to bring about the excitation of the K shells of Fe atoms. Such temperatures may be produced in flares. The series limit for the K shell of Fe is 1.4 Å. The abundance of elements heavier than Fe in the solar atmosphere is too small to contribute appreciably to the net X-ray flux. A limit to the X-ray spectrum arising from thermal excitation of the corona may therefore lie in the neighborhood of 1.4 Å for all flares larger than a certain critical magnitude. The rocket discovery of 1–2 Å X-rays in a typical Class 3+ flare implies that the wavelength limit is almost reached by such flares.

In support of the above hypothesis are the observations of Sudden Phase Anomalies (SPA). The SPA is a measure of the drop in the base of the D-region reflecting layer for long radio waves in the earth's upper atmosphere. A maximum drop of 16 km never appears to be exceeded in a wide variety of Class 3, 3+, or even in the rare cosmic ray flares. This height difference of 16 km is of the same order of magnitude as the difference in theoretical depth of penetration of the atmosphere by Lyman alpha ultraviolet rays and X-rays in the 1- to 1.5 Å range. Lyman alpha is responsible for normal D-region ionization. Although an increase in Lyman alpha may account for part of the increased D-region ionization during a flare, it cannot produce the very low-level ionization observed in the SPA. In order for Lyman alpha to produce a16-km drop in the base of the D region, the total solar Lyman alpha intensity would have to increase by a factor of 10^4. Since the flare region occupies at most 10^{-3} of the disk, the implication is that Lyman alpha in the flare region increases to 10^7 times the normal value. Such a flux density is virtually impossible astrophysically. X-ray flares can readily account for the magnitudes of observed depressions in the reflecting base.

Radio absorption measurements during Sudden Ionospheric Disturbances (SID) require a five to tenfold increase in total ionization in the absorbing region for Class 2 and 3 flares. The observed X-ray fluxes are adequate to produce such increases in electron density.

Scientific Results

The scientific results of the program to date are of considerable interest. New geophysical data on solar X-rays have been obtained for flares of Class 1+, 2, and 3+ magnitudes, as well as background data under no-flare conditions. From preliminary inspection of the telemetered data certain features of the X-ray emission are quite clear. A flare produces a marked increase in X radiation of short wave length, or hardening of the X-ray spectrum, compared to that of the quiet corona. The largest flare produced the shortest wavelength X-ray emission, about 2 Å. The total X-ray flux varied from about 10^{-3} ergs/cm^2/sec for the Class 1+ flare to about 10^{-2} ergs/cm^2/sec. for the Class 2 flare. An estimate has not yet been made of the flu in the Class 3+ flare but it appears tha hardness of the spectrum may play a mor important role than total flux in accountin for the associated SID.

In every case, an attempt was made t time the rocket firing with the expecte maximum phase of the flare. In each firing therefore, the first few minutes of flar development were by-passed. No evidenc has been obtained for large increases i Lyman alpha during any of the flare firings However, this does not justify ruling ou the possibility of a Lyman alpha flash ver early in a flare.

Field Operations

The field operation of the DAN Flar Project is of considerable interest as it con- trasts with other rocket launching opera-

Table 1. *Summary of Results of Rocket Flare Patrol Program*

IGY Rocket No.	Date	Altitude (feet)	Sun	Data	Comments
NN7.37F	7/ 1/57	306,000	Quiet	Background, aspect,* γ-rays. No X-rays below 100 km	NACA ignitor; ignitor very rough; large yaw & tumble
NN7.38F	7/ 3/57 0928Z	345,000	Class 1 No SID	Lα, γ-rays, aspect	NACA ignitor; ignitor very rough; large yaw & tumble
NN7.39F	7/15/57 1423Z	90,000	2.5 hr SID	Insufficient altitude, γ-rays	Modified NACA ignitor, failed to ignite Deacon
NN7.40F	7/23/57 1629Z	410,000	Quiet	Aspect, Lα, γ-rays	NRL ignitor plus closure & spinnerons; stable flight
NN7.41F	8/ 5/57 1210Z	40,000	Class 2+	Insufficient altitude	Pre-ignition of Deacon
NN7.42F	8/20/57 0949Z	320,000	Class 1+	Aspect, X-ray	NRL ignitor + closure; large yaw
NN7.43F	8/27/57 0854Z	40,000	Quiet	Insufficient altitude	NRL ignitor + closure; pre-ignition (0.1 sec delay)
NN7.44F	8/28/57 1321Z	410,000	Class 2+ ½ hr SID	Lα, aspect, γ-ray	NRL ignitor + closure; stable flight
NN7.45F	8/29/57 1412Z	420,000	Class 2 ½ hr SID	Lα, X-rays, aspect	NRL ignitor + closure; stable flight
NN7.46F	9/12/57	10,000	Class 2+ 2 hr SID	Insufficient altitude	NRL ignitor + closure; pre-ignition (0.06 sec)
NN7.47F	9/15/57 1327Z		Class 2	Battery failed at take-off	NRL ignitor + closure; visual & photographed flight appeared good
NN7.48F	9/18/57 1042Z	100,000	Class 3+ 2 hr SID	Insufficient altitude	NRL ignitor + closure; Deacon did not ignite
NN7.49F	9/18/57 1054Z	250,000	Class 3+ 2 hr SID	X-rays, aspect	NRL ignitor + closure; rocket tumbled

* Orientation of rocket with respect to sun.

ions. Except for the first few launchings, the ield crew has consisted of five to seven men. This crew has been made up partially of personnel from the NRL Optics Division and artially of employees of the Cooper Development Corporation (CDC), contractors o NRL. The NRL crew handled the preparation and installation of the rocket instrument heads, the monitoring of information from the solar observatories, the onitoring of radio fadeout, the firing of he rockets, the telemetering system, and he field analysis and interpretation of the data. They also made auxiliary photographic records of the rocket launchings in the interest of advancing the development of techniques for handling small rockets. The CDC field crew handled the preparation of the two-stage rocket, that is, fitting the crated Nike booster and Deacon bottles with fins and junction fittings, adjusting the rocket fins with spin tabs, preparing Deacon igniters, installing Deacon and Nike igniters, mounting the rockets on the launching frames, operating the launcher, and handling the repeated arming and disarming of the rockets during the daily operations of the group.

In the course of the program, several advances in the technique of using small rockets for research purposes have been accomplished. A new type of aerodynamic telemetering antenna, with uniform radiation pattern, was developed and gave perfect telemetering performance on all flights. Extensive data on the yaw behavior of small rockets above the restraining influence of atmospheric stabilization have been obtained. The effect of using no second-stage closure (NACA system) on ignition delay and subsequent rocket yaw has been observed and photographed, and a closure system for the two-stage trajectory configuration has been developed. The practicability of command firing of small rockets with only a 60-second delay has been proven. The practicability of rapid repeated firing of small research rockets from a single rocket launcher has been confirmed. Measurements of skin temperature were made. Data were accumulated on the effect of rocket yaw on altitude. Boosters have been visually tracked and some experimental information on the influence of wind on the rocket's trajectory is available. Much detail on rocket behavior is contained in the telemetering records yet to be analyzed.

The success of this project was made possible by the cooperation of the Navy personnel at Pt. Mugu, California. Cdr. O. E. Hearn, USN, designed the launching site and was responsible for all arrangements with the Navy for carrying out the project. The correlation of scientific rocket results with direct solar observations was made possible through the cooperation of Sacramento Peak, High Altitude Observatory, and Mt. Wilson personnel, who observed the sun through the long hours of the rocket operation and maintained the difficult communication links with the island.

Microcard Program for IGY Meteorological Data

The following article is based on material supplied by D. A. Davies, Secretary-General, World Meteorological Organization, Geneva, Switzerland.

The IGY Meteorological Data Centre, in the World Meteorological Organization, is publishing on microcards the essential meteorological data collected during the 18 months of the International Geophysical Year.

Microcards are standard-size library catalogue cards (75 x 125 mm, 3 x 5 inches) on

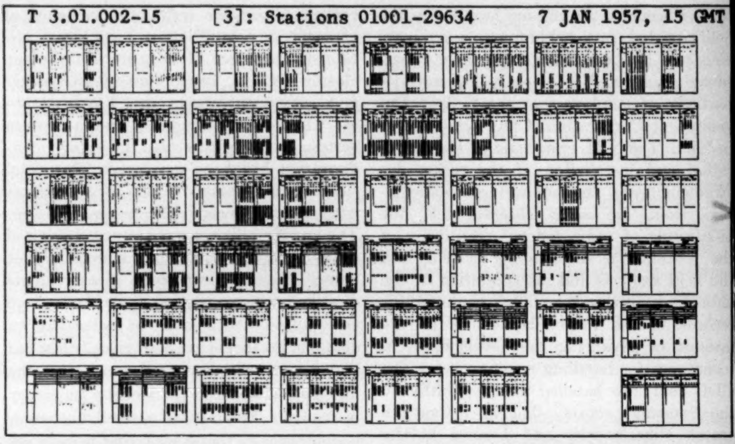

Fig. 2. *Typical WMO Microcard Used in IGY Meteorological Program (actual size 3" x 5").*

which a number of the original forms (40 to 96) are reproduced in greatly reduced size (see Fig. 2). A special microcard reader, which projects an enlarged image onto a tilted screen, is used for reading the data.

A complete set of microcards of IGY meteorological data consists of four parts, corresponding to the four different types of standard forms on which the essential meteorological data are being recorded. They are:

Part 1. Synoptic Surface Observations—Land Stations (Form No. 1)
Part 2. Synoptic Surface Observations—Sea Stations (Forms No. 2 and No. 2(b)
Part 3. Radiosonde and Rawinsonde Observations (Form No. 3)
Part 4. Upper Wind Observations (Form No. 4)

Description of the Four Types of Microcards

Form 1, Synoptic Surface Observations—Land Stations, contains 20 surface observations made at a single station during a period of five consecutive days (i.e., one pentade) at the synoptic hours 0000, 0600, 1200, and 1800 GMT. Each Part 1 microcard has room for a maximum of 96 reproductions of Form 1 arranged in eight rows of 12 forms each; however, the number of forms reproduced on any one microcard will vary between 70 and 90 in order to leave sufficient space for headings, additions, alterations, etc. The forms will be assembled according to the WMO station index numbers. Twenty-five microcards will accommodate the data from 2,000 surface stations; the surface synoptic observations recorded on Form 1 during the 110 pentades of the IGY will, therefore, require a total of 2,750 microcards.

Synoptic surface observations made at sea stations are being recorded on two variations of Form 2. Ships' reports will be written or typed on the basic Form 2, while on the other, Form 2 (b), they will be tabulated from punch cards. Forms containing observations made on board ships at the same synoptic hour will be published together on one or more microcards. It is estimated that about 4,400 Part 2 microcards, reproducing Forms 2 and 2(b), will be sufficient to publish all synoptic surface observations made at sea stations during the IGY.

Radiosonde and rawinsonde observations

re recorded on a standard form, Form 3, hich may contain the results of three or our ascents. Microcards on which these orms are reproduced, constituting Part 3 f the set, have room for 40 to 48 forms ar-anged in five or six rows of eight forms ach. Ascents made at the same standard ime will be grouped according to the WMO tation index numbers.

The largest of these groups in Part 3 will onsist of microcards reporting daily ascents ade at 0000 and 1200 GMT throughout the GY. Five to six microcards will probably e needed for each of these two main ynoptic hours, making a total of 5,500 icrocards for the whole of the IGY.

Reports of ascents made daily at 0600 and 800 GMT will be reproduced in another, maller group of about 220 microcards.

Additional ascent data gathered on Regu-ar World Days and in World Meteorological ntervals will be reproduced in a third group f about 280 microcards.

The total number of microcards on which adiosonde and rawinsonde observations ill be reproduced (Part 3) will, therefore, pproximate 6,000.

Upper wind observations are recorded n a standard form which has space for 10 bservations. The microcards on which these orms are reproduced, Part 4 of the set, ave room for 40 to 48 forms arranged in ive or six rows of eight forms each. Ascents made at the same standard time will be grouped in the sequence of the WMO station index numbers, preserving as far as possible the same basic regional layout for each of the four main standard times—0000, 0600, 1200 and 1800 GMT—during the whole of the IGY. Microcards containing upper wind data collected during the IGY (Part 4) will total about 5,000.

Complete Set of WMO Microcards for IGY

It is estimated that about 18,500 microcards (including a small margin for possible additions, etc.) will be required to reproduce the essential meteorological observations to be made during the IGY. These are distributed among the four basic data groups as follows:

Part 1—2,750 microcards
Part 2—4,400 microcards
Part 3—6,000 microcards
Part 4—5,000 microcards

A subscription price of $5,990 has been established for one complete set of the microcards. Prices for partial sets and individual microcards will be announced at a later date. Orders for microcards may be placed with the World Meteorological Organization, IGY Meteorological Data Centre, 1 Avenue de la Paix, Geneva, Switzerland. Further information about them may also be obtained from this address.

Ionospheric Studies Using Earth Satellites

A conference on study of the ionosphere by means of radio observation of earth satellites was held on November 5, 1957, at the Central Radio Propagation Laboratory (CRPL) of the National Bureau of Standards, Boulder, Colorado. Organized by the USNC-IGY, under the direction of A. H. Shapley, the conference brought together groups that had spontaneously initiated ionospheric experiments utilizing radio transmissions from satellites launched by the USSR.

The purpose was to enable these groups to discuss their progress, explore refinements in experimental techniques, plan future observations, and discuss problems of reduction and interpretation of measurements made with the first satellites.

Table 2. *Observation of Soviet Satellite Signals*

Agency	Signal Strength Data	Doppler Data	Interferometric and Other Phase-Difference Data	Direction Finding and Radar Data
BRL		20 mc; 0.1–1% slant range accuracy	Two 20-mc interferometers in plane of orbit	
Caltech	20, 40 mc; on tape	20, 40 mc		
DTM			40-mc phase-switching interferometer data for $\alpha 2$, from Oct. 4; also for β	
Geo. Inst.	20, 40 mc with WWV, from Oct. 4		40-mc total-power interferometer	
HAO	20 mc, 65 passes; on tape (12 in first 24 hours of $\alpha 2$)	20 mc; satisfactory data for 20 passes	20-mc total-power interferometer, Oct. 4–18	
Linc. Lab.	20 mc, Oct. 5–25; 40 mc, Oct. 6–25; exact measurement of frequencies	20, 40 mc; accuracy 2 secs in time, 10 miles in slant range		Radar with 2° x 2° beamwidth; same DF data taken at first; vertical incidence ionospheric soundings
NBS	20 and 40 mc, E-W and N-S; 100 cycle/sec recorder; low angle 40-mc rhombic antenna data; pulse studies	20 mc, 40 mc; calibrated against WWV: accuracy several cycles/sec	Phase-switching interferometers: 40-mc E-W, and 20-mc E-W (double baseline); 40-mc N-S total-power interferometer; continuous phase recording on 1000-ft. baselines; 20, 40 mc, E-W and N-S, circularly-polarized antennas	
Los Alamos	Tape records of $\alpha 2$, β	40 mc data using human ear discrimination; 3% accuracy in slope		
NEL			Data from Oct. 5 on N-S & E-W sets of 2 spaced antennas; MK I minitrack adaptation: 20-mc N-S and E-W signal recordings; 40-mc N-S and E-W phase recordings	
NRA			2 dipole E-W interferometers	
NRL		Some data obtained	Minitrack (in operation at Blossom Point, Lima, and San Diego); null times at 20 mc, continuous phase recording at 40 mc; WWV recorded on traces	Radio-telescope altitude data
ASEL and ASRPA	Data from Oct. 4 (aural Oct. 4–7)	Records for Oct. 6–8 at Fletcher's Ice Island, Oct. 8–9 at Thule, Oct. 6–8 on Grand Bahama Island, from Oct. 6 at Adak		Precision 20 and 40 mc; precision DF data from Oct. 5
SRI	20 and 40 mc from Oct. 4 on tape with WWV	Some 20-, mostly 40-mc data from Oct. 4; slant ranges; simultaneous Doppler observations of data		DF: 40-mc for more than one week; 106-mc radar observations
U of Ill.	20 mc on tape, Oct. 4	A few tapes	40-mc records from Oct. 5: N-S (5.45λ spacing), N-S (1λ), and E-W(6λ); 20-mc N-S (5.45λ) continuous from Oct. 6; N-S data on highspeed instrument to record detailed fading	

Table 2.—*Continued*

Code:
BRL: Ballistics Research Laboratory, Aberdeen, Md.
Caltech: California Institute of Technology.
DTM: Department of Terrestrial Magnetism, Carnegie Institution of Washington, D.C.
Geo. Inst.: Geophysical Institute, University of Alaska.
HAO: High Altitude Observatory, Boulder, Colorado.
Linc. Lab.: Lincoln Laboratories, Massachusetts Institute of Technology.
Los Alamos: Los Alamos, New Mexico.
NBS: National Bureau of Standards, Boulder, Colorado.
NEL: Naval Electronics Laboratory, San Diego, California.
NRA: National Radio Astronomy Laboratory, Green Bank, West Virginia.
NRL: Naval Research Laboratory, Washington, D. C.
ASEL: Army Signal Engineering Laboratory, New Jersey.
ASRPA: Army Signal Radio Propagation Agency, New Jersey.
SRI: Stanford Research Institute, California.
U of Ill.: University of Illinois.

Observations Reported

Representatives of some 24 laboratories and organizations were present at the conference. As an introduction to further discussion they were asked to give short accounts of their observations of the first two satellites, designated $\alpha 2$ and β. Table 2 presents very briefly a résumé of the experiments reported by those participating.

At the time of the Boulder conference, radio transmission from satellite $\alpha 2$ had ceased, but the conference date fell in the middle of the one-week period of transmission from satellite β. Consequently, the entries in the table refer primarily to studies of satellite $\alpha 2$, although in most cases the indicated observations were continued during the period of activity of β.

Signal strength data, as listed in Table 2 include times of appearance and disappearance of radio signals during individual satellite passes. These differ for the two frequencies of signals used. In accordance with theory, under ordinary conditions waves of both frequencies penetrate the ionosphere, but the higher-frequency waves should traverse the ionosphere at greater angles of incidence than those of the lower frequency, and should, therefore, be observed for a longer period of time at ground level. However, this theoretical behavior is actually found to be greatly modified by skip and by anomalous effects not understood at present. The signal levels themselves have been found to be subject to fluctuations, as explained below.

The Doppler effect (col. 3 of Table 2), is well known as the decline in pitch of a railroad train's whistle as the train flashes past the observer. As observed from a fixed ground station, the corresponding decrease in satellite radio frequency during a pass is not only a function of the velocity and position of the transmitting satellite relative to the receiver, but also, according to theory, it is to some degree a function of the ion density along the path between satellite and observer and in the immediate environment of the satellite itself. Hence, interest in such measurements is great.

Typical Doppler curves for $\alpha 2$, recorded at the National Bureau of Standards' Boulder Laboratories, are shown in Fig. 3. The more abrupt the curve, the closer the satellite passed the site of the receiver. Ionospheric effects are also contained in such curves, so that, conversely, if the satellite oscillator is stable and the precise orbit of the satellite is known, ionospheric densities can be deduced from the Doppler shifts. Useful Doppler observations need not be too involved since the human ear functions to excellent advantage in determining the general nature of such curves.

The principle of comparison of phases received over different paths as a means of position determination has been described in some detail in an article on Minitrack equipment in *Bulletin No. 2, August 1957*. Such interferometric observations (col. 4 of Table 2) are subject to fading or fluctuation effects and especially to refraction by

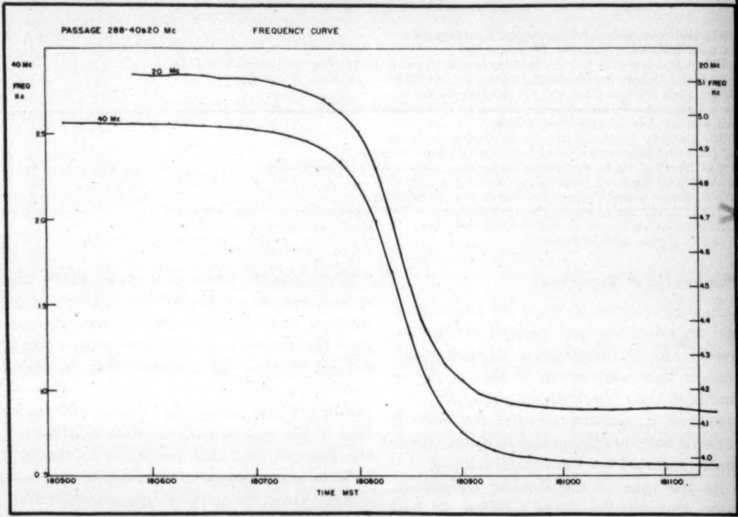

Fig. 3. *Doppler Effect at Table Mesa Site, National Bureau of Standards, Boulder, Colorado, on 288th Passage of Satellite 1957 α2 October 23, 1957.*

the ionosphere. Sometimes, so-called total-power interferometers have been used to subtract the fading effects introduced along the transmission path or caused by changes in the relative orientation of the satellite and the observing antennas. In this way, phase variations can be studied separately, without the hindrance of extraneous fluctuations. Interferometric measurements can also be very useful in determining the nature of the upper ionosphere, for, if a precise orbit is known, deviations from expected behavior may be attirbuted to specific ionospheric phenomena.

In Table 2 are listed radar installations and direction finding instruments. The latter provide data based on signal intensities received at different bearings. (A 400-mc, narrow-beam radar in operation at the Geophysical Institute, University of Alaska, is not listed; no satellite data were obtained there owing to lack of a sufficiently precise satellite-search ephemeris.) Radar observations of the final phase of satellite orbits would be especially useful. Integrated ion concentrations along radar paths can be deduced from the Faraday effect (rotation of the plane of polarization in the presence of a magnetic field). Thus, the hitherto unknown ion concentrations above the F2-layer maximum can be deduced if knowledge of the ionospheric structure below that level is available.

Although not all of the fifty or more persons participating in the conference had experimental data to summarize, a number of unusual events were reported.

—H. W. Wells of the Department of Terrestrial Magnetism, Carnegie Institution, reported the reception of strong 40-mc signals when the satellite was on the opposite side of the earth. He stated that the half-transit "ghosts" were clean signals and could not have been caused by an occasional cloud or sporadic-E propagation.

—R. M. Gallet of CRPL reported a

sudden decrease of 500 cycles/sec in the basic 40-mc transmission frequency of $\alpha 2$ at the time of the 250th pass, on October 21.

—Louis Burkhardt of Los Alamos noted that a decrease of about one kc in the 40-mc signal of $\alpha 2$ had occurred just before final fadeout. The fadeout itself was observed by several participants to have been gradual rather than abrupt.

—F. R. Dickson, of the Army Signal Radio Propagation Agency, indicated that during one 24-hour period there was continuous reception of satellite transmissions at Adak. (All *passes* during one such period were observed at the IGY South Pole Station.) Dickson also noted anomalies in DF records that appeared to be auroral in origin.

—Doppler frequency curves are sometimes distorted. Some curves plotted at the High Altitude Observatory were reported by D. Billings to have shown a lower maximum rate of decrease than would be consistent with initial and final rates of decrease. This is attributed to ionospheric effects. C. G. Little stated that one out of ten Doppler records at the Geophysical Institute, University of Alaska, shows distortion. Little and W. O. Roberts of the High Altitude Observatory agreed that frequency reversals of Doppler data are seen occasionally, although those observed in Alaska seem to be associated with auroral transmission and occur for only a second or two rather than as long as a minute.

The most general and significant problem of record analysis discussed was that of fluctuations and fading rates. R. N. Bracewell reported that amplitude records at Stanford showed faint CW transmissions between "beeps" received from $\alpha 2$ at long range. He also noted that in order to deduce ionospheric characteristics from observational records, fading owing to such mechanical factors as satellite spin or attitude would necessarily have to be extracted so that the influence of such factors as rapid auroral fluctuations or variations resulting from the Faraday rotation could be assessed. R. Jastrow of the Naval Research Laboratory, L. G. de Bey of Ballistics Research Laboratory, and R. S. Lawrence of CRPL, reported on the wide variety of phase and amplitude fluctuations observed. J. Herbstreit stated that continuous phase recordings with spaced antennas are potentially valuable for studying ionospheric turbulence. It was noted that some preferred periodicities seemed to be about 1½ sec and 4 or 4½ sec. It was pointed out that antenna polarities and orientations are such that a very subtle analysis of the records is required to arrive at a proper interpretation.

E. Hayden of the University of Illinois stated that observations frequently began with scintillations, which later changed to regular fading, leaving one-sec fluctuations superposed on a four-sec rate. Fade periods rapidly decreased as the satellite passed out of range. On 20-mc interferometer records, precursor fluctuation patterns were often observed in the afternoon before the actual interference pattern appeared. W. O. Roberts, of the High Altitude Observatory, stated that HAO records also showed such behavior, but in the opposite order. On some evening passes signal strength increased as the satellite receded, according to W. S. MacDonald, of the California Institute of Technology. It was agreed that maximum signal strength is not useful as an indication of time of closest approach.

Suggestions and Recommendations

Considerable discussion at the conference concerned the role radio amateurs might play in satellite observations. In general, it was felt that the observation of in and out times, rough signal strengths, and perhaps Doppler observations—preferably with a common, general, standard-reference frequency—might be useful, particularly in connection with long-range propagation effects. It was informally suggested that George Grammer, who was present as representative of the Amateur Radio Relay

League, might formulate the precise program. Amateurs would be asked to perform their own data reduction but the ARRL might act as a clearing house to accept and examine their reduced data.

Participants at the conference asked IGY satellite-tracking organizations to indicate the kinds of supplementary data which would be useful to them. They also requested that orbital and prediction data be distributed widely, rapidly, and in a form readily usable at each station; it was desired that precision estimates accompany the data. Observers were themselves asked to submit comparisons of satellite prediction and observation to the Smithsonian Institution and the Naval Research Laboratory.

The need for simultaneous optical and radio satellite observations was emphasized; any data fixing the orbit more precisely is helpful in extracting ionospheric information. Simultaneous ionosonde and radio observations would also be most useful. It was strongly urged that satellite transmission frequencies be stabilized as much as practicable to permit the extraction of the maximum quantity of ionospheric information from precision Doppler data. The desirability of having some future satellite transmissions at frequencies of the order of 20 mc, with known modulation as a control experiment, was recognized by all. There was also an extended discussion of the comparative usefulness of Doppler and Minitrack observations for obtaining orbital data.

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IGY BULLETIN

A monthly survey by the U. S. National Committee for the International Geophysical Year. Established by and part of the National Academy of Sciences, the Committee is responsible for the U. S. International Geophysical Year program in which several hundred American scientists are participating and many public and private institutions are cooperating.

First Sea Surface Gravimeter

The first successful surface measurements of gravity in the open sea were made on November 22, 1957, by J. Lamar Worzel, Assistant Director of the Lamont Geological Observatory at Columbia University, using a new sea gravimeter developed by Anton Graf of Munich. The instrument was mounted on a gyro-stabilized platform installed aboard the USS *Compass Island*. (The *Compass Island*, one of the few vessels on which a stabilized platform is installed, was made available for this work by Captain L. L. Schork of the U. S. Navy's Bureau of Ordnance.)

Gravity values for ocean areas have, in the past, had to be measured in submarines submerged to quiet depths. Difficulties in obtaining and fitting submarines for this purpose greatly restricted the accumulation of gravity data for the 80 percent of the earth's surface that is covered by water. The new sea gravimeter now makes it possible to take gravity measurements simply and expeditiously in moderately calm seas any place on the ocean surfaces of the earth, thus assuring that data long needed but difficult or impossible to obtain will now be available.

To date there have been only about 5000 measurements of gravity made at sea throughout the world. A device for multiplying the volume of such data is therefore of the greatest importance for the objectives of the IGY gravity program. This program seeks (1) to fill in the major gaps in a world gravity network, principally in the Arctic, Antarctic, and ocean areas, and (2) to relate existing networks, generally national in character, to each other so as to produce a first-order international network. Attainment of these objectives will greatly improve gravimetric mapping, which offers the fastest and most accurate method for linking all maps to a common reference system, and add much to knowledge of the earth's shape and the distribution of its mass.

Roughly half of the existing sea surface gravity measurements have been made by the Lamont Geological Observatory in the past 10 years, using pendulums carried in submerged submarines. Gravity measurements at sea were begun as recently as 1927 by Vening Meinesz, who developed a pendulum apparatus for use on the spongy soil of Holland. Meinesz found that his pendulums could be used in submarines to take gravity readings in the open sea, and it was he who made most of the 1,200 oceanic gravity measurements recorded by the end of World War II. Since the end of the war, British and Dutch scientists, in addition to those at Lamont, have conducted submarine gravity programs.

The new sea surface gravimeter has additional advantages over the standard submarine pendulums. Surface gravity measurements from the USS *Compass Island* were

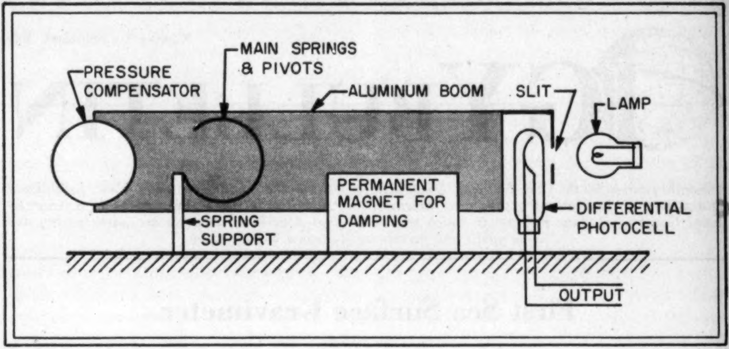
MAIN SPRINGS & PIVOTS
PRESSURE COMPENSATOR
ALUMINUM BOOM
SLIT
LAMP
PERMANENT MAGNET FOR DAMPING
SPRING SUPPORT
DIFFERENTIAL PHOTOCELL
OUTPUT

Fig. 1.

taken in nine hours, as compared with two days for earlier submarine measurements of comparable areas. The data were reduced in just one-half day, as compared with two weeks needed to adjust and compute data from submarine measurements.

The USS *Compass Island* left New York November 18 and returned November 22. To evaluate the accuracy of the Graf sea gravimeter, which had previously been tested on a surface ship only on a lake and the Adriatic Sea, the surface measurements were begun 200 miles southeast of New York on November 22, at a point where measurements had been taken aboard the submarine USS *Tusk* in 1947. The surface measurements were continued on a track which closely duplicated the *Tusk's*, moving from the deep ocean basin across the continental slope and onto the continental shelf, ending off Fire Island, New York.

The Graf sea gravimeter consists of a

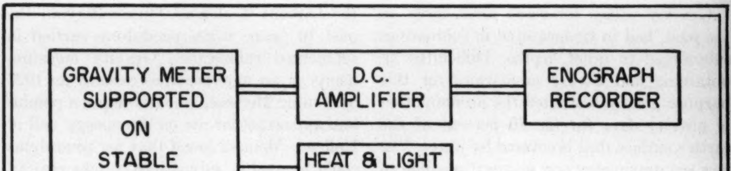
GRAVITY METER SUPPORTED ON STABLE PLATFORM
D.C. AMPLIFIER
ENOGRAPH RECORDER
HEAT & LIGHT POWER SUPPLY

Fig. 2.

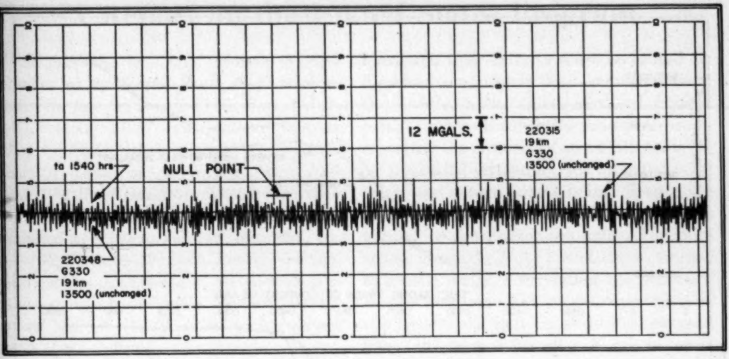

Fig. 3.

horizontal aluminum boom sprung and pivoted on horizontal cylindrical springs near one end (see Fig. 1). The position of the boom is determined by a differential photocell which is activated by a lamp illuminating a slit attached to the boom. The field of a large permanent magnet is cut by the aluminum boom, providing eddy current damping when the boom moves. The small instrumental volume results in air pressure compensation. The system is largely temperature-compensated; it is enclosed in a doubly-thermostated oven maintaining the temperature within about 0.01°C.

Figure 2 is a block diagram of the system. The output of the gravimeter is amplified in the d.c. amplifier, further damped electrically, and then recorded on an Enograph recorder, a self-balancing potentiometer-type recorder.

The operation of the equipment consists of establishing the meter on the stable platform and levelling it. The springs are adjusted to bring the boom close to the instrument null point, as indicated by the Enograph recorder. The wave accelerations appear as fluctuations of the recorder trace about a mean position. The damping of the overall system is such that wave accelerations with periods of six seconds are reduced by a factor of 10,000, and wave accelerations with periods of ten seconds are reduced by a factor of 3000. The time constant of the highly-damped system is such that a change of gravity requires five minutes for its complete registration.

The dial reading at the null point is computed from the dial setting combined with the mean position of the boom indicated by the recorder. The scale constant of the meter and observations at base points permit one to calculate the gravity reading for each five- to ten-minute section of the record.

Certain types of corrections are made for each observation. The ship has a centrifugal acceleration owing to the rotation of the earth; it is necessary to make a correction (the Eötvös correction) of this acceleration because of the east-west component of the ship's speed. Later, the effects of current can be estimated from the ship's navigation plot. The resultant observed gravity is then available for such anomaly computations as desired.

Figure 3 shows approximately a one-half hour section of the record made on board USS *Compass Island* The wave periods were about eight seconds and maximum vertical accelerations of 140,000 milligals peak to peak are indicated as about 20 milligals peak to peak on the record.

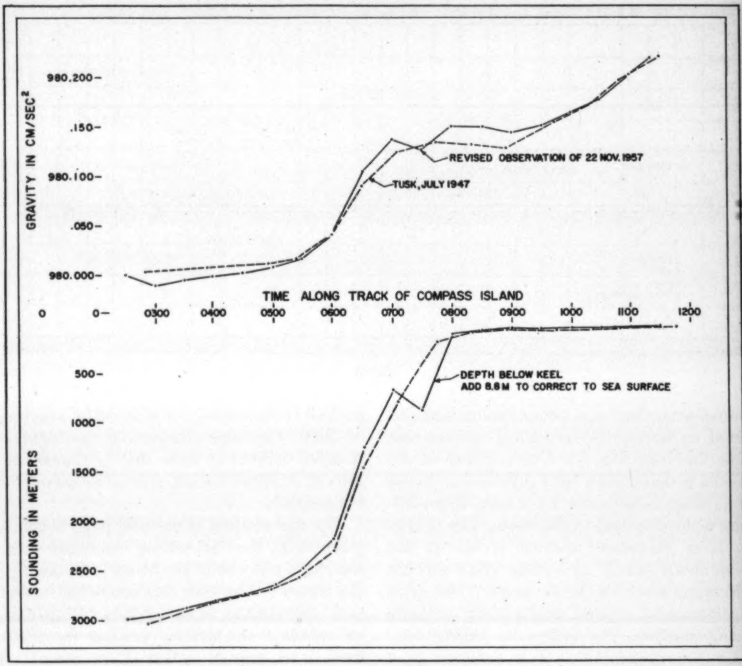

Fig. 4.

Figure 4 shows a plot of the observed gravity values at half-hour intervals on USS *Compass Island* and the observations of USS *Tusk* projected to the track of USS *Compass Island*. The bottom half of Figure 5 shows the corrected soundings obtained on each ship at the same time that the gravity readings were made. The comparison of these data is considered extremely satisfactory in view of the differences in the observation positions and the much poorer navigation data accompanying the USS *Tusk* observations with respect to both position determination and the Eötvös corrections.

Lamont scientists plan to continue to test the Graf sea gravimeter throughout the IGY, and they hope that it will eventually take its place aboard all oceanographic research vessels and become a standard method of gravity measurement.

A Report on the United States Program

The following is a brief account of some activities in the United States IGY program during the first five months of the Year, 1 July to 30 November, 1957. It is condensed from an article entitled "International Geophysical Year: A Report on the United States Program," by Hugh Odishaw, Executive Director of the US National Committee for the IGY, published in Science, *Vol. 127, No. 3290, pp. 115–128, January 17, 1958. Background material on the dimensions of the various programs in which early IGY findings are described here may be found in the first several issues of the Bulletin.*

Physics of the Upper Atmosphere

Solar Activity: On the eve of the IGY's beginning, the first major solar flare of the program, that of 28 June 1957, was observed at the Krasnaya Pakhra Observatory in the Soviet Union. A message was flashed to the World Warning Agency operated for the IGY by the National Bureau of Standards at Fort Belvoir, Virginia, which declared a state of Alert beginning at 1600 UT, 28 June. (Alerts are declared when there is probability of solar disturbances. When the probability is high that terrestrial disturbances will also occur, Special World Intervals are promulgated calling for increased measurements of solar-terrestrial phenomena.) The first such interval in IGY was broadcast on June 29, to commence at 0001 UT 30 June. Throughout the world observations of the sun were intensified, and balloons and instrumented rockets were sent up by many nations to observe the increased ultraviolet and X-radiation and to monitor cosmic ray intensity. Observations and measurements were speeded up to record more carefully and fully the northern and southern lights, to measure disturbances in the earth's magnetic field, and to probe the ionosphere.

It had long been thought, but not heretofore conclusively established, that absorption of radio signals during such periods of maximum solar activity must be caused by increased ionization in the lower atmosphere. On 4 July, radio signals received from a rocket fired up through the ionosphere demonstrated the presence of an additional layer of ionization extending for about 12 mi below the normal lowest point. Even more remarkably, the rocket data showed that the normal ion distribution throughout the ionosphere above the D, or lowest, layer, seemed to remain undisturbed during the blackout. In another recent IGY rocket experiment, it was ascertained that the additional electron layer was caused by solar X-ray emission associated with the occurrence of solar flares.

In another portion of the IGY program, at the Mount Wilson Observatory in California, measurements are being made of the magnetic field of the sun at its surface. It has already been found that magnetic fields at the sun's surface may be very high, as much as 8,000 times that of the earth's field at the equator. These magnetic fields are thought to play a very important role in disturbances and storms on the sun's surface as well as in sunspots.

It has been suggested, but not previously established, that the magnetic effects we observe on earth during magnetic storms may be due to great electric currents, of perhaps several hundred thousand amperes, flowing around the earth high in the atmosphere. Two of these currents are believed to circle the North and South magnetic poles while the third circles the earth at the geomagnetic equator.

Stations in South America and in the Pacific Ocean—at Guam and Koror in the Western Pacific, and at Jarvis, Palmyra, and Fanning Islands in the Eastern Pacific—were established especially to study the existence of the so-called "electro-jet." The electro-jet is believed to be the equatorial electric current, but narrowed down into a "neck" of limited horizontal dimensions with consequent increased current density and intensified activity at local noon. The US

Coast and Geodetic Survey, which operates many of the magnetic observatories established by the United States, reports tentative confirmation of this phenomenon. Initial data from Koror reveal the existence of the equatorial electro-jet and its rather limited horizontal extent.

Aurora and Airglow: The 39 stations and hundreds of amateurs participating in the United States program have already had much to observe. The fact that the IGY was scheduled for a period of expected maximum solar activity has greatly enhanced the value of the program, for already three of the largest solar flares (class 3+) have resulted in extensive auroral displays visible as far south as Havana, Cuba. Synoptic maps have been prepared depicting all auroras observed and reported from the United States during the months of July and August. This is the first time that such a complete description of auroral data has been assembled for the use of geophysicists studying auroral and such related phenomena as ionospheric and geomagnetic effects.

English scientists at the University of Manchester have reported that coordinated radar observations indicate that auroras occur simultaneously in the Northern and Southern Hemispheres, a condition long believed to be true by scientists, but not previously established. Additional polar radio data which provide further evidence on this question have been obtained in the United States program.

The systematic reduction of the variations in the intensity of the night airglow is proceeding. Charts of the "patchiness" and movement of night sky luminosity resulting from oxygen emissions are being produced on a routine basis from IGY observations.

Ionospheric Physics: New information about the farthest reaches of the atmosphere is being obtained from the study of "whistlers"—whistle-like sounds which can be detected at very low radio frequencies. These signals, originating in lightning flashes at the surface of the earth, swing out thousands of miles along the earth's lines of magnetic force before they return to earth in the opposite polar hemisphere. Early IGY experiments demonstrated that the ion density and molecular concentration along the whistler path at altitudes of as much as twice the earth's radius must be much greater than formerly anticipated. Indeed, there seems to be confirmation for the theory that the earth's atmosphere extends far beyond the level where it had been previously thought to "end" and that there may be a very tenuous atmosphere—the sun's corona—filling all the space between the earth and the sun.

Other records of previously unexplained radio noise at very low frequencies have stimulated the hypothesis that solar particles arriving in the very high atmosphere transfer energy to very low frequency radio waves there. According to this hypothesis, the radio signals thus amplified are the very low frequency radio emissions observed at ground level. Data now being gathered will throw further light on this hypothesis, which is based on the traveling wave tube principle as noted by Roger Gallet.

Ionospheric characteristics are deduced from the analysis of echoes arising from the reflection of radio pulses transmitted to the ionosphere at vertical incidence. Since the IGY began there have been several major solar events that caused disruption of long-range, short-wave radio communications which depend upon reflections from the ionosphere. For the first time, a synoptic picture has been obtained of the growth and decay, station by station, of such fadeouts.

The principal, regular variation in the ionosphere is the diurnal one. Ionization density increases during the day, when the sun is present, and decreases at night. What would happen to the ionosphere during long absences of solar radiation and the nature of any diurnal variation during such periods have been subjects of speculation. Only at or near the geographical poles can these questions be examined, and the South Pole affords the best platform for an observatory. Investigations during the last year at the

South Pole Station of the United States have yielded interesting results: in spite of the absence of the sun, the electron concentration seems to remain very high throughout the polar night; moreover, there is a diurnal variation that can only, it appears, be associated with geomagnetic activity. The evidence so far obtained suggests that ionospheric behavior in the two polar regions is essentially the same. Analysis of these observations may appreciably alter our concepts of the ionization and recombination processes in the atmosphere.

Cosmic Rays: These electrically-charged particles, which bombard the earth continuously and from every direction, are markedly influenced by the earth's magnetic field: low energy particles are deflected toward the vicinity of the two geomagnetic poles, and only the more energetic ones penetrate at the middle latitudes.

Investigations at the 20 United States cosmic ray stations have already provided interesting results. The work of scientists from the University of Chicago has shown that the location of the line where the cosmic ray intensity is a minimum—the "cosmic ray equator"—deviates systematically from the geomagnetic equator. The experiments leading to this result began in 1954–55 when a neutron pile detector was installed aboard the USS *Atka*, which conducted a reconnaissance of the Antarctic prior to the establishment of IGY stations in following years. Measurements were made on the trip down, around Antarctica, and back; these measurements were repeated in the 1955–56 and 1956–57 Antarctic seasons aboard the USS *Arneb* and were supplemented by aircraft flights in a zigzag pattern around the geographical equator in October 1956. These studies showed a 40° to 45° shift to the west of the inclined cosmic ray equator with respect to the magnetic equator. J. A. Simpson suggests that this warping may well indicate the presence of important magnetic fields, probably of extraterrestrial origin, which alter the trajectories of the incoming primary cosmic ray particles.

Typical of international cooperation in this program during the IGY is the Swedish-Canadian-American cosmic ray experiment carried out aboard the Swedish merchant ship M/S *Lommaren* sailing between Sweden and the Union of South Africa.

Preliminary balloon flights in and near Minnesota with ionization chambers have shown that, at constant altitude, there is a strong latitude effect. This is so strong that latitude changes as small as 7 mi can be detected by cosmic ray measurements. Other balloon experiments at Fort Churchill and Thule have shown that cosmic rays of lower energy (less than about 2 Bev) effectively disappeared during the present period of high solar activity, with ionization at high altitudes down to half the value it had in 1954 or 1955.

Perhaps one of the most interesting observations made in the course of IGY cosmic ray experiments was that of relatively soft radiation in the high atmosphere, associated with primary auroral radiations. Rocket and balloon flights have led to the positive identification of the soft radiation: it is X-radiation in the range between 10^4 and 10^5 electron volts. There appears to be good correlation between the presence of such radiation and solar, magnetic, and auroral activity. The effect is probably a secondary one; it is believed that incoming auroral particles create the X-rays by bombardment of atmospheric particles.

There were 29 rockets fired in the pre-IGY test period. These included Aerobees, Rockoons and Nike-Cajuns. Firings took place at the newly erected facilities at Fort Churchill (with Canadian cooperation) as well as at White Sands, New Mexico, Guam, and from shipboard off the California coast and in the North Atlantic. These firings were successful, and the preliminary information gained was of considerable value in the final detailed planning of the schedules for firings during the IGY period.

The United States IGY program in rocketry actually began on 5 July 1956 at Wallop's Island, Virginia, when the first IGY test rocket was fired successfully. To date, 83 rockets have been fired during the IGY. Included have been those in programs conducted at Fort Churchill (nine Aerobees, five Nike-Cajuns); White Sands (two Nike-Cajuns); Point Mugu, San Nicolas Island, California (13 Nike-Deacons); a shipborne operation in the Arctic (18 Rockoons) and a shipborne operation in Pacific and Antarctic waters, concluded in mid-November (36 Rockoons). The following are some preliminary findings:

1. A firing at Fort Churchill indicated that the first atmospheric temperature maximum occurred at an altitude of about 60 km. Normally, this maximum is found below 50 km at lower latitudes, indicating that, at northern latitudes, the rise is more gradual. (Temperatures decrease up to the stratosphere, rise during the next 20 to 30 km, decrease through the next 30 km, and then rise again.)

2. A rocket instrumented for ionospheric studies was sent through a polar radio blackout for the first time. Data were obtained which indicated that a very dense D-region exists at a significantly lower altitude and with a much greater density than is found at lower latitudes.

Another firing at Fort Churchill during the summer of 1957 measured electron distribution in the ionosphere up to an altitude of 250 km during a polar blackout. The results of this experiment confirmed theories that the D-region of the ionosphere is primarily responsible for radio blackouts.

3. During a series of firings with Aerobees and Nike-Cajuns instrumented for studies of pressure, temperature, and density, it was determined that the distribution of pressure and temperature in the atmosphere at high latitudes is much different than it is at lower latitudes. Many of these rockets attained altitudes greater than 200 km, and thus the first density measurements made at high latitudes were recorded. Launchings were made during both summer and winter, day and night. The resulting data indicate that the density of the high atmosphere is under strong solar control. There appear to be a latitude effect, a seasonal effect, and a strong diurnal effect; none of these effects appears at lower altitudes at Fort Churchill or lower latitudes.

4. An experiment with a mass spectrometer at Fort Churchill appears to confirm the belief that diffusive separation of gases under gravity is present above 100 km at that latitude. Below this point the gases in the atmosphere appear to be well mixed.

5. During July and August 1957 the DAN rocket flare patrol program took place at Point Mugu, California. This program was primarily directed toward determining the radiation source of the fadeouts resulting from flares observed on the disc of the sun. For the first time, measurements were made of X-ray and ultraviolet bursts from the sun during a solar flare. These data will help in explaining radio blackouts, which are present during periods of unusually high degree of ionization and which are closely associated with solar flares.

6. During the shipboard firings in the Arctic, an excellent survey was made for the first time of auroral particles and their association with actual auroras. Also conducted for the first time at high latitudes were magnetic field measurements.

Satellites represent an extension of rocketry useful in probing the high atmosphere. The USSR launched its first satellite on 4 October 1957. This satellite, a sphere nearly 23 inches in diameter and weighing about 184 pounds, carried transmitters broadcasting on frequencies of 20 and 40 mc/sec. The second Soviet satellite was launched on 3 November. Weighing about 1120 pounds, the last rocket stage was reported to carry two transmitters (20 and 40 mc), a dog, and instruments to measure satellite temperatures, ultraviolet light, X-rays, and cosmic rays. The initial period of the second satellite's revolution was 103.7 min with an apogee of approximately 1056 mi and perigee of about 150 mi.

The United States program is proceeding

according to schedule. The Navy has responsibility for the rocket system and launching in the Vanguard series, the Army for the Jupiter-C series. The IGY Committee of the Academy is responsible for the scientific aspects, both internal experiments and the radio and optical observation programs. Two types of satellites have been designed: test spheres for use during the test period for the Vanguard rocket system and equipment-laden satellites thereafter for both the Vanguard and Jupiter-C vehicles.

Earth's Heat and Water Regimen

Meteorology: For the first time, synoptic meteorological charts of the vast unknown continent of Antarctica are being drawn on a daily basis at the Antarctic Weather Central, operated at Little America with the aid of scientists from a number of nations. As a result, weather forecasting has already been markedly improved in the Southern Hemisphere. Aside from the forecasting and synoptic aspect, the scientific value of the observations in Antarctica are potentially of great value in understanding atmospheric circulation and its relation to solar radiation and topography.

The Antarctic is the coldest place on earth. The continent itself is elevated and mountainous, the South Pole being almost 10,000 ft above sea level. Last September 17, the South Pole Station reported the lowest temperature yet recorded, 102.1° below zero.

In the Antarctic meteorology program, large neoprene balloons have been sent to altitudes of over 80,000 ft, and the average is about 60,000 ft. Meteorological balloons sent up at 112 non-Antarctic United States stations are reaching altitudes ranging from 85,000 to 107,000 ft.

In addition to these broad-scale programs, several specialized programs are underway, and preliminary results have been received. For example, there is in Little America an instrument which measures the minute quantity of ozone in the air at the ground level. Ozone mainly occurs in a layer-like region about 15 mi high in the earth's atmosphere. Some ozone diffuses to the ground or is formed at lower levels by ultraviolet light. It has been noticed that, at Little America, there is about 25 per cent more ozone at the ground than there is in New Mexico. Although ozone is a minor constituent of the atmosphere, it is thought to play an important role in the circulation of the high atmosphere, because of the energy it can absorb and release.

Another minor constituent of the atmosphere which may play a major role in climatic changes is carbon dioxide. Our industrial civilization burns tremendous quantities of fossil fuel each year, pouring millions of tons of carbon dioxide into the atmosphere. Most of this is absorbed by plant life and by the waters of the oceans, but there is the possibility that eventually the carbon dioxide content of the atmosphere will rise enough to affect the world's climate. It has been found already that the concentration of carbon dioxide in the Antarctic is about the same as in non-industrial areas over the rest of the world.

Glaciology: Technical advances and discoveries have already been made in the two greatest reservoirs of ice in the world, Greenland and Antarctica. In Greenland, scientists and engineers of the US Army's Snow, Ice and Permafrost Research Establishment have perfected techniques for drilling deep holes in the ice with hollow drills, much as an oil well is drilled, to obtain a "core" of ice. The first hole was drilled in Greenland in 1956 and reached a depth of over 1000 ft. The second hole was successfully drilled in 1957 in Greenland, and a similar operation is now under way in the Antarctic in Marie Byrd Land.

The recent boring in the ice of Greenland reached a depth of 1438 ft. A complete series of cores 4 inches in diameter was obtained from the first 1040 ft. Below this depth, recovery of the core is difficult because the release of strains as the ice is drilled causes the ice to shatter. Dissolved gas, which is under great pressure in the ice at these depths, also causes trouble because it bursts through pockets in the ice, increasing the amount of shattering. However, a core was obtained from 1200 to 1220 ft, and another from 1320 to 1338 ft. These cores are being studied with great care in the laboratory, for they are an invaluable index of climate and precipitation over the past many hundreds of years. Their layers are studied in much the same fashion as tree rings. From the first hole in Greenland, the 1912 layer was identified by the ash from a volcano which erupted in Alaska. The dust from the great explosion in 1883 of the volcano Krakatoa, in the East Indies, will be a help in checking the dating of the annual layers of precipitation in the cores. Because precipitation is lower in the Antarctic than in Greenland, it is expected that this ash layer will be found at a depth of about 150 ft in Greenland and at about 60 ft in the Antarctic.

The great ice sheet of the Antarctic, over 6 million square miles in extent, cannot be studied in anything but a spotty fashion. However, teams of glaciologists, seismologists, and support personnel are traveling by tractors and special over-snow vehicles thousands of miles across the ice in a series of traverses to obtain the profile of ice thickness across the continent and to attempt to learn something of the underlying terrain, or formation of the ice-covered earth. For example, after the Byrd Station was established some 600 mi from Little America by a tractor party, a traverse team then crossed the ice shelf from Little America and continued to Byrd Station, exploring the ice as it went. During this first traverse, it was discovered that Byrd Station, at an elevation of about 5000 ft above sea level, stands upon ice almost 10,000 ft thick. Further explorations will reveal whether this is a frozen fjord or inland sea and what part of this submergence may be due to the bending inward of the earth's crust as a result of the weight of the ice.

United States scientists at two locations in the Arctic basin are now making studies of the melting of the ice pack, the freezing of new ice, and the general relations between the state of the ice and the local climate.

Drifting Station A is now located in the region of latitude 85.30°N and longitude 170°W, 310.5 miles from the Pole. It is on the ice pack itself, on a floe a few miles in area and only some 7 to 12 ft thick. Scientists there have noted that during the past summer season about 12 inches of ice on the upper surface have melted, while as much as 18 to 24 inches of new ice have frozen on the bottom of the floe. This observation will be placed in proper perspective when all the information on radiation from the sun, ocean currents, and temperatures of the air, ice, and oceans has been studied.

Recently, in a test of instrumentation developed by J. C. Swallow of the National Institute of Oceanography in England, the *Atlantis*, a research vessel of the Woods Hole Oceanographic Institution, and the British research vessel, *Discovery II*, explored the eastern edge of the Gulf Stream and for the first time were able to map the underlying flow of water. They found that, at depths of about 6500 ft, there was either very little or erratic movement; shallower depths showed set to the northeast, as expected, but at about depths of about 9000 ft, the current sets in the opposite direction—southwest—at the relatively high speed of 8 mi per day. The Swallow neutral buoyancy float was tracked electronically in this work, providing a new technique which enables IGY oceanographers the world over to map both surface and relatively deep currents.

Several United States ships have already made extensive cruises for the IGY. The work of the *Atlantis* has already been mentioned. The *Crawford*, also of the Woods Hole Oceanographic Institution, made a four months' cruise in the *Atlantic*. The *Crawford* reoccupied many stations taken years ago by the German ship *Meteor* and discovered that there have been pronounced changes in the amount of oxygen dissolved in the Atlantic in the region of 15° South latitude. The difference in oxygen content over the past 30 years may mean that deep bottom water is not being formed as fast now as it was previously, but further data and analysis are needed for proper interpretation of the present observations.

The *Vema*, a research vessel operated by the Lamont Geological Observatory of Columbia University, has completed an extensive cruise in the Southern Atlantic Ocean, working along the coasts of South America and Africa, and crossing the Atlantic at high southern latitudes between Argentina and Capetown. The *Vema* cooperated with the *Bahia Blanca*, a survey vessel of Argentina, in making explorations of the submarine crust by seismic methods. Considerable marine biological work was also done, and Lamont has reported that living organisms—a small shellfish and a worm one-fourth of an inch long—were recovered alive from depths of 13,200 and 16,200 ft respectively. Lamont scientists believe these to be record depths for retrieval of live marine samples. (The *Vema* has since left New York on a second cruise.)

In the Pacific, the *Brown Bear* of the University of Washington worked in the Northeast Pacific Ocean last summer. The deep currents in that area were studied. The *Horizon* and *Baird*, research vessels operated by the Scripps Institution of Oceanography of the University of California, left San Diego in October for a two-ship, five-month expedition through the Central and Southeast Pacific. They will make seismic explorations of the submarine crust, study surface and deep currents, take bottom samples and occupy about 40 oceanographic stations, where water samples down to great depths will be obtained for later analysis of chemical content. The *Jakkula*, of the Agricultural and Mechanical College of Texas, will cruise in the Caribbean Sea and western Atlantic in the summer of 1958.

Another part of the IGY oceanography program is the study of the mean sea level over the period of the IGY. It has been found from study of tide data that there seems to be an exchange of water between the Northern and Southern Hemispheres as the seasons change. New tide gauges are being set up to supplement the existing network: instruments are already operating in Bermuda, Iceland, and the Azores in the Atlantic, and in the Caroline, Marshall, and, with the cooperation of French scientists, at French islands in the Southeast Pacific. A station is in operation on Pitcairn Island under the supervision of a descendant of one of the mutineers of HMS *Bounty*.

Geophysicists on Drifting Station A, in the Arctic Ocean, reported on August 12, 1957, that the ice floe on which their station is established had floated over an underwater mountain range, or ridge, rising more than 5,000 ft above the ocean floor. The ridge was discovered in the course of routine seismic depth soundings and gravimetric measurements when the station was at 82° 54′ N, 167° 28′ W—about 850 mi northwest of Barrow, Alaska, and about 550 mi from the North Pole—drifting generally toward the Pole. The soundings indicated a rapid decrease in ocean depths, from more than 10,000 ft to slightly less than 5,000 ft. Increased gravity values indicated a corresponding substantial compensation in the crustal mass. On November 23, 1957, the station recrossed the ridge and was able to confirm its original report. Scientists of the Soviet Union are doing similar work on two stations in the Arctic Basin.

In the Antarctic the ships of the various nations supporting scientific stations on the continent engage in oceanographic observations enroute to and from the area. Thus, USSR and New Zealand ships have added to our knowledge of these waters. Ships of the US Navy Task Force 43 are also exploring the coast, charting the bottom, and taking bottom and water samples for future study.

Earth's Structure and Interior

Seismology: Several new types of seismographs with wide range and high sensitivity have been located at observatories throughout the world. The Lamont Geological Observatory has constructed ten special long period seismographs and has installed most of them at observatories ranging from Hawaii to Fiji and from Bermuda to the Antarctic. These long-period instruments are sensitive to surface waves of periods of about 400 sec, generated only by the very largest earthquakes. These wave-lengths are so long that they penetrate to the interior of the earth, and in fact, the whole earth itself may be set into vibration. Recently, workers at Lamont have discovered the existence of certain intermediate waves with periods of about 100 sec. These waves, which were previously only known in the crust in continental structures, have been identified now in the mantle, or the next layer beneath the crust. These waves permit better resolution of structural details than the longer 400-sec waves, and study of their propagation is expected to provide new information on the distribution of materials in the interior of the earth.

Seismologists from the Department of Terrestrial Magnetism of the Carnegie Institution of Washington worked on exploration of the roots of the Andes Mountains in South America last summer and fall. They have found roots of unsuspected depths and are now working on their data to obtain better understanding of the crustal structure under this great mountain chain.

Seismologists of the US Coast and Geodetic Survey have installed new seismic equipment in the Pacific at Truk and Koror and have been obtaining records of Pacific earthquakes. These new stations, together with those in the Antarctic, will add significantly to our knowledge of seismicity and the structure of the earth.

The first successful measurements of gravity on the open sea were made on November 22, 1957, by J. Lamar Worzel of the Lamont Geological Observatory, using a sea gravimeter developed by Anton Graf of Munich. In the past, gravity measurements for oceanic areas required measurements aboard submarines at quiet depths below the surface. The difficulty of obtaining and fitting submarines for this purpose made it impossible adequately to survey the seas: only about 5,000 such measurements have been made throughout the world. The new instrument, mounted on a gyro-stabilized platform, will make it possible to obtain data simply and quickly anywhere at sea with a precision of one part per million, similar to that attainable on land.

IGY data

The preceding sections suggest the nature of the IGY activities as shown by the US IGY effort in the first few months of the program. With 67 nations cooperating in the endeavor and some 10,000 scientists and technicians making observations and measurements at more than 2,000 stations, the volume of data stemming from the program will be considerable. To ensure the safety of the raw data and their accessibility, the international IGY committee has approved the establishment of three world data centers—in the US, in Europe, and in the USSR.

Each data center will acquire a complete set of all IGY data. Each center will archive and index its compilation of data, holding it accessible to research workers. Schedules for the orderly flow of data into the centers have been arranged. These schedules vary, depending upon the nature of the data in a given discipline and upon the definition of a reasonable "lot" of data to simplify the handling problems. A "lot" of data may be one month's observations in one field or several months' in another.

The procedures for handling data and forwarding them appropriately involve a series of steps of the following kind: (i) collection of a "lot" of data at a field station, (ii) transmittal of the "lot" to the home laboratory of the field station, (iii) checking of field data at the home laboratory, (iv) transmittal to one of the World Data Centers, (v) copying of the data by one World

Data Center for the other two and appropriate transmittal, and (vi) indexing and archiving at World Data Centers.

The data centers are in operation, and data are flowing into the centers. The steps outlined above lead to a peak early in 1958, a steady 18-month plateau through at least the first six months of 1959, followed by a "clean-up" period extending probably into the first quarter or so of 1960.

Acknowledgment: The preparation of this narrative would not have been possible without the cooperation of many scientists and institutions engaged in the IGY program. Although some of them are mentioned in the text, it has not been possible in this summary to refer to all. The United States IGY program has only been possible because so many individual scientists as well as public and private institutions have participated and cooperated in the endeavor. Particular acknowledgment is made to members of the Academy's IGY staff who have helped in the preparation of this report: Stanley Ruttenberg, Phillip Mange, John Hanessian, Jr., and John Truesdale.

Satellite Telemetry

This article is based upon material furnished by Whitney Matthews of the Naval Research Laboratory and George H. Ludwig of the State University of Iowa.

In order that non-recoverable satellites may be used for direct observations in space, they must be equipped with telemetering systems—systems designed to record observations made by the satellite's instruments, to encode those observations for transmittal to ground stations and then to accomplish the actual transmission. Without such systems, only ground-based satellite experiments could be conducted. With them, instruments may be used to make observations directly in space, unhampered by an intervening atmosphere.

Special Requirements

Requirements for a telemetering system to be used in an earth satellite are much the same as for any such system, but qualities normally considered desirable become essential in satellite telemetry. The cost of putting a satellite into orbit, the longer period available for telemetry, and the impossibility of maintenance all place unusual emphasis upon reliability. The high cost in vehicle power and weight required to place each additional ounce in orbit makes it necessary to keep telemetering weight factors extremely low. To keep the system operating as long as possible on self-contained batteries, power needs must be held to the minimum.

A new and major problem in the design of satellite telemetry systems is that of providing memory devices. Since US satellites will pass over nearly two-thirds of the earth's surface, it is impractical to establish ground stations in sufficient numbers to assure continuous monitoring and recording of satellite transmissions. With ground stations limited to reasonable numbers, the probability of obtaining significant data at the particular times when satellite signals can be monitored is not high enough—particularly in view of the nature of many of the phenomena to be studied. Therefore, memory devices are needed to store information collected during an orbit and to release data on receiving an appropriate signal from a ground station.

Each of the earth satellites to be launched by the United States during the International Geophysical Year will contain a different combination of scientific experiments. One group of satellites will telemeter data continuously, as it is observed. A second group, either using satellite-borne tape recorders for storing synoptic data or requiring relatively high-power consumption for making measurements, will carry "command" receivers to provide data transmission upon interrogation by ground stations.

With one exception all telemetered data from US-IGY satellites will be transmitted by amplitude modulations (AM) of the signals from the radio transmitter operating at 108 mc.

Lyman-alpha Package

Instruments carried in satellites of one design will measure ultraviolet radiation in the Lyman-alpha region of the solar spectrum, satellite temperature, and the impact upon the satellite of micro-meteoric particles. The instrumentation has been developed by the Naval Research Laboratory.

Solar radiation always contains energy i the Lyman-alpha region, with marked increases occurring during periods of sola flares. The Lyman-alpha satellite experiment will study both the Lyman-alph radiation from the quiescent sun and th peak values associated with solar flares. Solar Lyman-alpha radiation will be measured by an ionization chamber sensitiv only in the desired region of the solar spectrum.

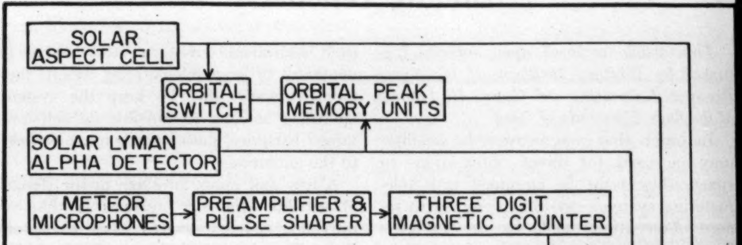
SOLAR ASPECT CELL
ORBITAL SWITCH
ORBITAL PEAK MEMORY UNITS
SOLAR LYMAN ALPHA DETECTOR
METEOR MICROPHONES
PREAMPLIFIER & PULSE SHAPER
THREE DIGIT MAGNETIC COUNTER
HIGH FREQUENCY INPUT SELECTOR
RF OUT
TRANSMITTER
MODULATOR
TELEMETRY ENCODER
TIME INTERVAL INPUT SELECTOR
THERMISTORS
PRESSURE GAGES
EROSION GAGES
CALIBRATION & IDENTIFICATION

Fig. 5. *Block Diagram of Telemetry System for the First US-IGY Artificial Earth Satellite.*

In order to interpret the data recorded by the ionization chamber, the aspect, or orientation, of the satellite with respect to the sun must be known. Aspect information will be supplied by signals from silicon solar aspect cells located in the equator of the satellite.

Both internal and external satellite temperatures will be measured by means of thermistors located inside the instrument package and on the outer shell near one pole and at the equator.

The remainder of the experiments in satellites of this type are concerned with collisions between the satellite and micrometeoric particles. Three, and possibly four, types of measurements will be made. The first type will use small erosion gauges, consisting of thin film resistors coating a glass attached to the outer surface of the satellite. By monitoring the resistance of these gauges it will be possible to detect wearing away of the resistive elements by minute particles colliding with the satellite. A cadmium sulfide detector, consisting of a photo-resistive element covered by an opaque material, may be substituted for one of these erosion gauges. In sunlight, the resistance of this element will be a function of the amount of opaque material removed from the sensitive element by collision with these microscopic particles.

The third micrometeor experiment uses a group of sensitive microphones as detecting elements. Signals from these microphones, which are attached to the skin of the satellite, will drive counting circuits associated with the telemetry system; this in turn, will transmit data continuously, providing the cumulative number of collisions.

In addition to the telemetry channels required for transmitting the above data, other channels will be used to monitor battery voltages and provide calibration and identification.

Fig. 5 shows the flow of information from the detecting elements through the telemetry system and transmitter.

Signal Codes: The telemetry encoder system for the Lyman-alpha package transmits a continuous series of high-frequency audio bursts. A complete set of all input signals, called a "frame" or "scan," contains 16 bursts and 16 spaces between bursts. Intelligence is carried in (1) the burst frequency, (2) the duration of the burst, and (3) the duration of the interval

Table I. *Telemetry Channel Assignments: Lyman-Alpha Environmental Satellite*

Burst No.	High Frequency Burst		Burst Duration		Interval Between Bursts	
	Channel	Function	Channel	Function	Channel	Function
1	A	Instantaneous Lyman-α	A1	Polar erosion A	A2	Battery volts
2	B	Solar aspect	B1	Differential pressure	B2	Short calibrate
3	A	Instantaneous Lyman-α	A1	Polar erosion A	A2	Battery volts
4	B	Solar aspect	B1	Differential pressure	B2	Short calibrate
5	A	Instantaneous Lyman-α	A1	Polar erosion A	A2	Battery volts
6	B	Solar aspect	B1	Differential pressure	B2	Short calibrate
7	C	Meteor count, units	C1	Long calibrate	C2	Battery volts
8	D	Meteor count, tens	D1	Package temperature	D2	Polar skin temperature
9	A	Instantaneous Lyman-α	A1	Polar erosion A	A2	Battery volts
10	B	Solar aspect	B1	Differential pressure	B2	Short calibrate
11	A	Instantaneous Lyman-α	A1	Polar erosion A	A2	Battery volts
12	B	Solar aspect	B1	Differential pressure	B2	Short calibrate
13	A	Instantaneous Lyman-α	A1	Polar erosion A	A2	Battery volts
14	B	Solar aspect	B1	Differential pressure	B2	Short calibrate
15	E	Meteor count, hundreds	E1	Polar erosion B	E2	Equator skin temperature
16	F	Peak Lyman-α	F1	Equator erosion	F2	Cadmium sulfide cell

between bursts. Thus, 48 potential information channels are provided, even though only 17 different data signals will be transmitted. Burst frequencies lie between 5 and 12.5 kc. Burst durations and blank intervals can vary from 4 to 30 milliseconds, although the dynamic ranges of many intervals are restricted to permit additional telemetry time for the solar Lyman-alpha experiment.

The telemetry channel assignments currently planned are shown in Table I. Transmission on Channels A and B, presenting solar Lyman-alpha and solar aspect signals are repeated several times during a scan. This frequent repetition—together with high-frequencies which permit continuously-variable signals to follow instantaneous changes—provides the necessary information from the input devices. Technical considerations dictate a similar repetition on the associated time interval channels A1, A2, B1, and B2.

The general character of a set of calibration curves for a typical telemetry encoder is shown in Fig. 6.

Cosmic-Ray Package

The satellite carrying the cosmic-ray experiment developed by the State University of Iowa will be launched by a vehicle developed by the US Army.

The radio transmission and telemetering system for the cosmic-ray satellite is being produced and assembled at the Jet Propulsion Laboratory of the California Institute of Technology.

At present, two different sets of instruments or "payloads" are being prepared. One set measures cosmic rays, meteoric density, and satellite temperatures. The other payload provides for these same measurements but adds a tape recorder, which will be geared to a ground interrogation system. The particular payload in use will be announced when the satellite is launched.

Cosmic-ray experiments: The measurement of cosmic-ray intensity outside the atmosphere of the earth and over a wide range of latitudes will provide new knowledge about these particles and about the earth's geomagnetic field. A single satellite-borne Geiger counter has been designed to measure the total cosmic-ray intensity without respect to direction. The instrument includes a storage system, which accumulates a record of the average counting rate for short periods of time. The time required for one orbit can be split into any number of segments and the average intensity for each segment can be assigned with a statistical uncertainty depending on the number of segments—the greater the number of segments the less the uncertainty.

The data to be obtained from such a system are useful for the (a) determination of the effective geomagnetic field; (b) study of time variations of primary radiation intensity, including their correlation with solar and magnetic observations and with the intensity of secondaries observed at ground stations; and (c) provide for the first time a comprehensive geographical survey of primary radiation.

Measurements of density of meteoric matter: Impact microphones (as used in the Lyman-alpha satellite) and erosion gauges, will be carried in the cosmic-ray satellite for measurements of the density of minute meteoric particles. Some of the erosion gauges are grid-like structures electrically connected in parallel. When one of the grid wires is hit by a particle physically large enough to break the wire, the over-all resistance of the string changes in a step-wise manner. Also included in the set of gauges is one composed of a very thin film of resistive material. The total resistance of this gauge will change slowly as the material is removed by the "sandblasting" action of cosmic dust, which travels at a very high velocity relative to that of the satellite. The gauges for density measurement of meteoric material were developed and provided by the Air Force Cambridge Research Center.

Telemetry equipment: Each of the payloads described above for cosmic-ray satel-

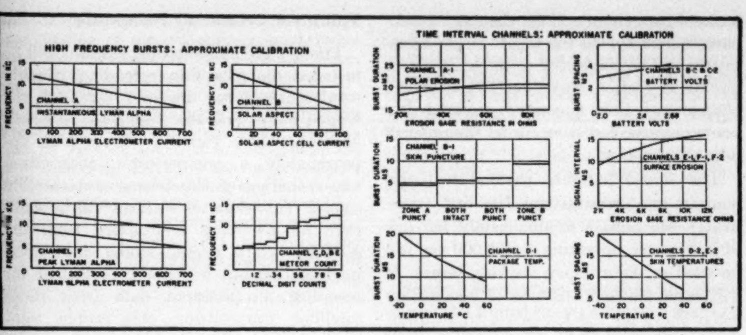

Fig. 6. *Representative Calibration Curves for a Typical Lyman-α Satellite Telemetry Encoder.*

lites will contain two transmitters; one will operate on the primary tracking frequency of 108.000 mc, and the other on 108.030 mc. Each of the two transmitters in the first payload will operate continuously and over four simultaneously used channels. One transmitter, of the Minitrack type, using a turnstile antenna, will radiate approximately 60 mw of power on 108.030 mc. It will operate from a battery supply which should enable it to transmit for approximately two weeks. The telemetering will be by AM over standard RDB telemetering Channels 2 through 5 (518 to 1320 cps).

The other transmitter will radiate approximately 10 mw of power on 108.000 mc. Its battery supply should enable it to operate for approximately two months. This transmitter will also carry information over four channels on the same RDB telemetering frequencies—in the form, however, of small-deviation phase modulation. The antenna for this transmitter will be formed by electrically splitting the satellite payload shell and driving the two pieces, thus generating a linearly polarized signal.

Although eight different telemetering channels will be available, two of these will be used in duplicate; therefore, only seven types of information will be carried. The higher-power transmitter will carry two temperature measurements: channel 2 (518–602 cps) will carry a measurement of the temperature of the outside of the payload case somewhere near the pole, and channel 3 (675–785 cps) will carry a measurement of the temperature of the interior of the transmitter. Channel 4 (888–1032 cps) will carry information derived from an impact microphone measuring the frequency of collision with micrometeors. Channel 5 (1202–1398 cps) will carry cosmic-ray information, and is of the most interest so far as telemetry reception from other parts of the world is concerned.

Channel 5 will carry information concerning measurement of the instantaneous ionization caused by cosmic radiation. The instrumentation consists of a Geiger-counter tube operating into a scale-of-32 circuit (a circuit in which 32 input signals generate one output signal). The output of the last scaler circuit controls the frequency of the telemetering subcarrier oscillator. The tone of the oscillator will change each time a new count goes into the last circuit of the scaler. The tone will shift back and forth every time 16 total counts have been received. This is expected to happen on the order of once per second.

The information from the impact microphone will be carried in a similar manner, the output of the microphone going into a scale-of-two circuit. The channel 4 subcarrier oscillator on the higher-power transmitter will be connected to the scale-of-two circuit in such a way that the tone will change each time a count is received. Impacts are expected to occur on the order of once every few seconds.

The second satellite payload will also contain two transmitters. The first transmitter will radiate approximately ten mw of power, and, operating on 108.000 mc, will be used as the primary tracking source. It will carry the four channels of information listed above for the low-power transmitter. This payload will also include a radio receiver for interrogations from primary IGY ground stations. The cosmic-ray instrumentation in the package includes a magnetic tape recorder for the purpose of recording cosmic-ray information during each orbit. Upon interrogation from the ground, the second transmitter will switch on; the tape-recorded information will be sent over this transmitter. The higher-power transmitter will again operate on 108.030 mc with a radiated power of approximately 60 mw. As in the case of the first payload, the low-power transmitter will send through a linearly polarized antenna, the high-power one through a turnstile.

Volunteer Telemetry Recording

Primary ground recording stations will be installed along a line extending roughly north-south down the east coast of the United States and the west coast of South America. These stations will provide approximately a one-per-orbit observation and recording of the telemetered satellite signals. This chain of stations will be sufficient for recording information from the satellites which release stored data upon interrogation but will not be sufficient for recording all pertinent data from those satellites transmitting observations continuously.

With the cooperation of British National Committee for the IGY and of local groups who will operate the equipment, two special telemetry receiving stations have been established in strategic positions near the geomagnetic equator at Ibadan, Nigeria, and at Singapore.

The US National Committee for the IGY solicits the assistance of all persons and organizations equipped to make tape recordings of satellite signals. Instructions on recording techniques and procedures for forwarding the tapes to the cognizant organizations are covered in the January 1958 issue of QST, the journal of the American Radio Relay League.

IGY Satellite Program Notes

The following report is reproduced from Science, *Vol. 126, p. 1334, Dec. 27, 1957.*

Soviet Satellite Carrier Rocket

On 8 December 1957 the president and the chief scientific secretary of the U.S.S.R. Academy of Sciences addressed a cable to the president of the U.S. National Academy of Sciences regarding the rocket carrier body of the first artificial earth satellite, which was launched on 4 October 1957. A similar cable was addressed on 9 December to Joseph Kaplan, chairman of the U.S. National Committee for the International Geophysical Year, by Academician I. P. Bardin, president of the Soviet IGY Committee. Because the substance of these two cables is identical, only the first is quoted:

DETLEV BRONK, *President*
National Academy of Sciences

According to available data some not entirely burnt remnants of the first earth satellite rocket have been scattered along a line including Alaska

and the west coast of North America. A thorough investigation of the not entirely burnt rocket remnants and the knowledge of the exact places of their fall are of great scientific significance as they provide valuable data concerning phenomena occurring when satellites enter the denser atmospheric layers. The USSR Academy of Sciences asks all the USA scientists to communicate the data concerning the fall of the rocket remnants and to send the remnants which were found to the Academy of Sciences Moscow USSR.

President of USSR Academy of Sciences
ACADEMICIAN A. N. NESMEYANOV
Chief Scientific Secretary of USSR Academy of Sciences
ACADEMICIAN TOPCHIEV

Although no evidence had come to light indicating that the rocket body of the first satellite had fallen in North America, a review of all available data and reports was initiated on 6 December when press dispatches from Moscow indicated that the U.S.S.R. believed the carrier body may have fallen on this continent. The results of this review, as of 11 December, were negative, and, on the same day, the president of the National Academy of Sciences accordingly addressed the following reply to the U.S.S.R. Academy:

PRESIDENT A. N. NESMEYANOV
Academy of Sciences of U.S.S.R.
Moscow

Reference your message and message Bardin to Kaplan our review thus far of sightings and trackings of satellite and investigation of reports of objects sighted do not indicate rocket or remnants fell in United States or its territories. We have no reports of finding of any such bodies. Your request being transmitted to trackers and others. It will be helpful if you can provide data you mention as available to guide our further search.

DETLEV W. BRONK, ***President***
National Academy of Sciences U.S.A.

Several observation programs are under way in the United States as part of the IGY effort in the tracking of all satellites. Photographic and visual tracking responsibilities have been assigned to the Smithsonian Astrophysical Observatory, 60 Garden St., Cambridge 38, Mass. Radio tracking responsibilities have been assigned to the Naval Research Laboratory, Washington 25, D.C. Reliable information on satellite sightings would be welcome. Photographic and visual data should be addressed to the Smithsonian Astrophysical Observatory and, similarly, radio data to the Naval Research Laboratory.

HUGH ODISHAW

USNC-IGY

Thule Neutron Monitor Station

This report is based on material provided by Martin A. Pomerantz of Bartol Research Foundation. The Thule monitor was constructed by the Foundation and is operated by the U.S. Army Signal Corps.

The neutron monitor installation in Thule, Greenland (76.5°N, 68.8°W) was completed and put into operation on 27 August, completing an Arctic chain of three neutron monitor stations. Observations made at Thule are particularly significant because this station, at geomagnetic latitude 88°N, is closer to the geomagnetic pole than any other neutron monitor installation.

Because of the deflecting effect of the earth's magnetic field, more cosmic rays reach the surface of the earth in high geomagnetic latitudes than in lower latitudes. Only high-energy atomic particles can reach the earth at the geomagnetic equator but the velocity requirement is reduced as the poles are approached.

Most of the cosmic rays that reach sea level are mesons—the so-called hard component. These particles are unstable and disintegrate a short time after they have been produced in interactions between the relatively high-energy primary cosmic rays and the atmosphere at very high altitudes. Their intensity near sea level depends in a very complicated manner on continually changing meteorological conditions throughout the atmosphere up to the point of origin.

In contrast, the nucleonic components, although comprising only a small fraction of these secondaries that reach the earth's surface, consist of protons and neutrons produced in the atmosphere by incoming low-energy cosmic rays and do not display the meson dependence upon meteorological conditions. Hence, by confining attention to the nucleons much information can be obtained about the geographic distribution of cosmic rays and of the earth's magnetic field.

A neutron monitor of the type installed at Thule detects the secondaries of the relatively low-energy cosmic rays, upon which the effects of magnetic conditions in the vicinity of the earth are most pronounced. A decrease in cosmic-ray intensity, as a consequence of either deflection or deceleration of these particles, is often associated with magnetic storms. Rapid increases in the cosmic-ray intensity sometimes occur simultaneously with eruptions on the solar disk. These often coincide with ionospheric disturbances causing radio blackouts.

The basic arrangement for measuring the intensity of the nucleonic component comprises a structure, called a "pile," in which several neutron detectors (boron trifluoride proportional counters containing BF_3 gas enriched with B^{10}) are embedded. The pile itself, consisting of lead and paraffin, contains a material of high atomic weight (lead) in which incoming nucleons can interact; a number of neutrons are produced in each of the resulting explosions. A neutron moderator (paraffin) slows these disintegration products down and retains them until ultimately they pass through one of the proportional counters that serve as neutron detectors. In some respects, this structure resembles an atomic reactor, except that in this case, the nuclear fuel is the nucleonic component of cosmic rays.

Each of the counters embedded in the pile actuates completely independent electronic circuits, so that the failure of any single component is easily recognizable. The scaled counts are tallied by a printing numerical register, as well as by an operation recorder pen which enters a pip on a continuously-moving chart driven by each counter. A chronometer with electrical contacts causes the reading on the register, and the corresponding time, to be printed on tape every 15 minutes. The impulses from the counters are also combined and introduced into a counting-rate computer, which indicates the average number of counts per minute. This is recorded on a chart continuously moving at a speed of six inches per hour. This makes it possible to correlate the time-variation of any unusual changes in the cosmic-ray intensity with other geophysical or solar disturbances.

A detailed comparison of time variations and distinctive events occurring near the geomagnetic pole, but at widely different longitudes, is being carried out with two other stations located at Resolute Bay, (74.7°N, 94.9°W) and at Murchison Bay, Spitzbergen (80.0°N, 19.0°E). These are under the direction of D. C. Rose, National Research Council of Canada, Ottawa, and A. E. Sandström, Fysiska Institutionen, Upsala, Sweden, respectively.

Transactions
American Geophysical Union

VOLUME 39 APRIL 1958 NUMBER 2

The Establishment of a Calibration Standard for Gravimeters in Eastern Canada and the United States

M. J. S. Innes

Abstract—A program of gravimeter measurements for the establishment of a suitable gravity standard in eastern Canada and United States is described. It is shown that the consistency of nine independent measurements of the gravity differences between stations forming a north-south line from Ottawa to Washington is highly satisfactory and that this line is suitable for calibration purposes. The gravity differences depend fundamentally upon a gravimeter calibration made against values of gravity at Cambridge pendulum stations in Canada.

The combined gravimeter results lead to a value of -501.44 ± 0.25 mgal for the difference in gravity between the Dominion Observatory, Ottawa, and building of the Department of Commerce in Washington. Although this determination agrees within the limits of error with recent Gulf pendulum results, it is concluded that more pendulum work is required before an absolute basis for this calibration line may be adopted.

Introduction—Considerable progress in the development of a satisfactory gravity standard for North America has already been achieved. In 1952 and 1953 the Dominion Observatory employed pendulum apparatus on loan from Cambridge University to establish gravity at eighteen points over a wide latitude range between Mexico City and Fairbanks, Alaska [*Garland*, 1953, 1955]. These measurements, which involve a change in gravity exceeding 4000 milligals, have been repeated, for the most part at identical sites, by United States scientists [*Rose* and *Woollard*, 1955] using quartz pendulums of the Gulf Oil Company. Comparison of the two sets of data [*Innes*, 1957; *Gilbert*, 1957] reveals systematic discrepancies which are believed to reflect errors in estimating sub-base values to which yearly sets of measurements were referred. While these differences have yet to be resolved, the Mexico-Alaska line of pendulum values is expected to provide an accurate gravity standard for the North American continent and to make an important contribution toward the establishment of a homogeneous world gravimetric network as recommended by the International Gravimetric Commission in Paris [*Coron*, 1954].

The difficult accessibility of this line in Canada, however, limits its usefulness as a direct standard for the calibration of gravimeters, particularly those instruments having a limited range. Portions of the line have been useful in providing suitable control for local surveys, but generally distances to it, and between successive pendulum stations, are too great to carry out gravimeter calibrations as frequently and regularly as might be needed. Experience has shown [*Innes* and *Thompson*, 1953] that the calibration factors of gravimeters, particularly those of the North American type, are subject to considerable change with time. Recent investigation indicates that such changes sometimes occur over periods of short duration and are usually related to overheating of the instrument following the failure of a thermostat relay. To ensure consistent results in regional gravimeter work, calibration checks must therefore be carried out periodically, the requirements being at least two calibrations per year, preferably one just prior to the field survey and the other immediately after its completion.

A series of stations extending along a north-south highway passing through Ottawa, from Prescott, Ontario, to Maniwaki, Quebec, and having an overall range of 124 milligals [*Saxov*, 1956] has served for a number of years as a provisional standard for the comparison of gravimeters employed by the Observatory. In 1953 it was considered that the usefulness of this line as a suitable reference standard for eastern Canada might appreciably be increased by extending its range. Accordingly a gravimeter program was initiated the following summer to establish a series of stations between Maniwaki and Senneterre, Quebec (see Fig. 1).

About the same time a redetermination with modern pendulum equipment was being carried out [*Garland*, 1953, 1955; *Rose* and *Woollard*, 1955], between the National Reference Stations of Canada and the United States, the former being located at the Dominion Observatory in Ottawa and the latter in the building of the Department of Commerce in Washington, D. C. It was decided therefore to abandon for the time being the program of measurements north of Ottawa and to concentrate on extending the calibration line south to include observations at important gravity stations in Washington. The objectives of this plan, although not entirely independent of each other, were three-fold: (1) to establish a highly reliable line of gravimeter stations between Ottawa and Washington (involving a change in gravity of about 500 mgal) to serve as a suitable, readily accessible gravity reference standard; (2) to provide an independent measure of the Ottawa-Washington gravity difference; and (3) to assess the reliability of the new pendulum determinations. This investigation has been satisfactorily

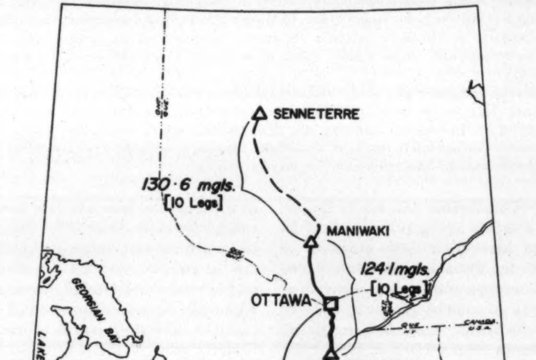
SENNETERRE
130·6 mgls.
[10 Legs]
MANIWAKI
124·1 mgls.
[10 Legs]
OTTAWA
GEORGIAN BAY
LAKE HURON
PRESCOTT
LAKE ONTARIO
SYRACUSE
501·4 mgls.
[25 Legs]
LAKE ERIE
BINGHAMTON
PITTSTON
NEW YORK
HARRISBURG
WASHINGTON

FIG. 1 – Location map of calibration line

completed and a detailed account of the results follows.

The measurements—The measurements were made with three instruments: North American Gravimeter 137, North American Gravimeter 85, and Worden Gravimeter 44. Complete forward looping procedure, the scheme being that stations A, B, C, for example, are occupied in the order A-B-A-B, B-C-B-C, etc., was followed for all measurements. The distances between successive stations were kept sufficiently small, less than 30 miles on the average, to permit an accurate estimate of zero drift for each instrument and at the same time to allow exclusive use of the short range dial of the Worden instrument.

The gravimeter observations were carried out on three separate observing programs, in October 1954, August 1955, and November 1955. Each program involved a complete coverage of the line between Ottawa and Washington and required about ten days' time and 2500 miles of automobile travel. By observing with three gravimeters concurrently at all stations it was hoped to obtain three independent sets of results from each observing program which could be matched to provide reliable values of gravity.

Descriptions of stations—In Ottawa, the National Reference Station for Canada has for many years been defined as the upper surface of a cement pier located in Room No. 2 in the basement of the Dominion Observatory. All relative gravity measurements within Canada have been based on a value of 980.622 cm/sec^2 for this station, obtained by direct comparison with Potsdam in 1928 [*Miller*, 1931]. The geodetic coordinates and height of the pier (referred to Geodetic Survey of Canada bench mark 125-A) are 45° 23′ 38.4″ N, 75° 42′ 56.4″ W, and height 271.68 feet.

In 1954 the gravity division was transferred from the Observatory building to the new Geophysical Laboratory (see Fig. 2 and 3). Although all future pendulum work is to be carried out in the Geophysical Building, the site of the original pendulum pier in the Dominion Observatory will continue to serve as the National Reference Station for Canada.

The new site for pendulum measurements is located in a temperature controlled room (Room 8) in the basement of the Geophysical Laboratory. The pendulum pier which is four feet square is situated in the center of the room, with its upper surface at floor level. It is made of concrete set about seven feet in subsoil, and has no contact with the surrounding basement floor. The geodetic coordinates of the new pendulum pier are 45° 23′ 41.9″N, 75° 42′ 52.9″W, and height 257.14 feet.

Two gravimeter stations in the vicinity of the Dominion Observatory have been well connected

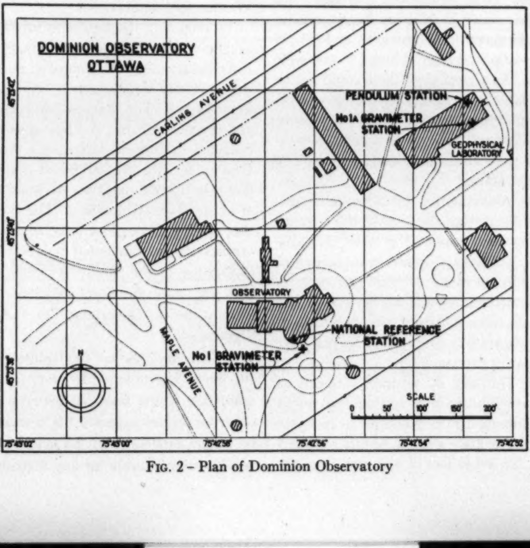

FIG. 2 – Plan of Dominion Observatory

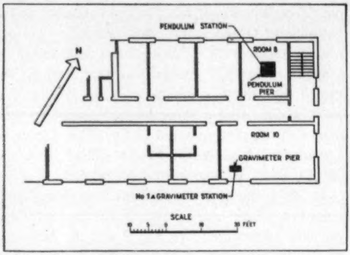

FIG. 3 – Plan of Geophysical Laboratory

to the National Reference Station. These subsidiary sites have proved convenient for international gravimeter ties and for control of local surveys. Gravimeter Station 1 is located in the center of the cement apron immediately outside the main entrance to the Dominion Observatory building. Its coordinates are 45° 23′ 38.2″ N, 75° 42′ 56.2″W, and height 274.22 feet.

Gravimeter Station 1A is the upper surface of a cement pier in the southwest corner of Room 10 in the basement of the Geophysical Laboratory (see Fig. 3). Its geodetic coordinates are 45° 23′ 41.6″N, 75° 42′ 52.8″W, height 259.44 feet.

Between Ottawa and Washington, apart from the differences of gravity involved, accessibility for observation using automobile transport was the chief criterion used in selecting the gravimeter sites. On the first trip to Washington in 1954, 27 intermediate stations were established to complete the connection. As a number of these could not be recovered on later trips because of new construction, local traffic disturbances, etc., it was necessary to establish new stations. As a result a total of 35 stations were established during the course of the three operations.

To facilitate re-occupation by other investigators diagrams illustrating the sites of the gravimeter bases have been drawn (Fig. 4–6). The distances to the gravimeter bases from points of reference, usually portions of buildings such as post offices, churches, schools are shown in the diagrams. While these distances are nearly exact, neither the configuration of the buildings nor their scale is necessarily precise.

The results—The lack of accurate connections between sites of fundamental stations has often led to much uncertainty in attempts to compare and evaluate the relative gravity results of different observers. To avoid loss of accuracy in correlating data the important Ottawa sites described above have been interconnected with great accuracy. In addition ties have been made to the laboratories of the National Research Council of Canada, both the Sussex Street laboratory where absolute measurements of gravity are in progress, and the Applied Chemistry building on the Montreal Road. The results of these connections are summarized schematically in Figure 7. The probable error of each gravity difference, estimated from the closure errors of the two closed circuits, is ± 0.03 mgal. The adopted values for the Ottawa sites on the basis of these results are given in Table 1.

Gravity differences between Ottawa and Washington are summarized in Table 2 which shows the results between Gravimeter Station 1 in Ottawa and Gravimeter Station 37, near the main entrance of the East Building of the National Bureau of Standards in Washington. To permit an independent evaluation of the measurements and to facilitate later revision, should this be necessary, a complete list of the gravity differences observed with each instrument is given. The stations between which the gravity differences have been measured are indicated in the first column and may be identified by reference to Table 3. A total of 36 gravity intervals have been determined, but as pointed out previously, only 27 segments are required, on the average, to complete the Ottawa-Washington connection.

To eliminate discrepancies arising from inconsistencies in calibration, the results of the three instruments have been compared over the complete range of the measurements, using a method of least squares. The statistics of these comparisons are given in Table 4. The gravity differences obtained in August 1955 using North American Gravimeter No. 137 and based upon a calibration factor of 0.23916 mgal per division, were accepted as a provisional standard. The justification for this will be given in a later section. The uncertainties of the calculated values of the relative calibration factors are very small, all less than 0.01 pct, and therefore contribute a negligible amount to the uncertainty in the final gravity differences.

Agreement between the values obtained with the three instruments is very satisfactory. Examination of the residuals between standard and observed values suggests the remaining errors to be purely random, with no marked suggestion of non-linearity of scale for any instrument over the

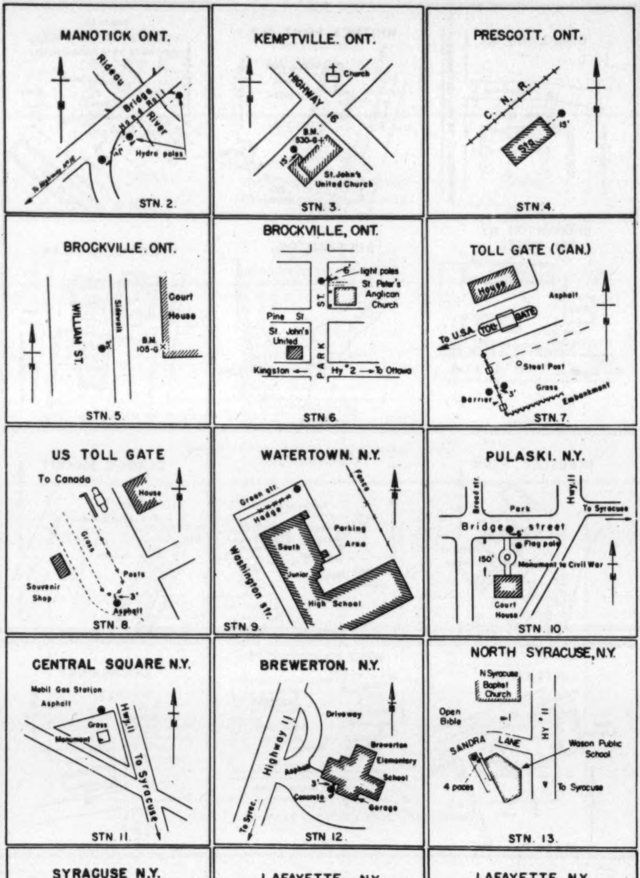
MANOTICK ONT.
Rideau
Bridge
Hand Rail
River
Hydro poles
To Highway
STN. 2.
KEMPTVILLE. ONT.
Church
HIGHWAY 16
B.M. 530-G
15'
St. John's United Church
STN. 3.
PRESCOTT. ONT.
C. N. R.
Stn
15'
STN. 4.
BROCKVILLE. ONT.
WILLIAM ST.
Sidewalk
Court House
B.M. 105-G
STN. 5.
BROCKVILLE, ONT.
6'
light poles
St. Peter's Anglican Church
ST.
Pine St
St. John's United
PARK
Kingston
Hy 2
To Ottawa
STN. 6.
TOLL GATE (CAN.)
House
Asphalt
To U.S.A.
TOLL GATE
Steel Post
Grass
Embankment
Barrier
3'
STN. 7.
US TOLL GATE
To Canada
House
Grass
Souvenir Shop
Posts
3'
Asphalt
STN. 8.
WATERTOWN. N.Y.
fence
Green str.
Hedge
Parking Area
South
Junior
High School
Washington str.
STN. 9.
PULASKI. N.Y.
Broad str.
Park
Hwy. 11
To Syracuse
Bridge street
Flag pole
150'
Monument to Civil War
Court House
STN. 10.
CENTRAL SQUARE N.Y.
Mobil Gas Station
Asphalt
Grass
Monument
Hwy. 11
To Syracuse
STN. 11.
BREWERTON. N.Y.
Driveway
Highway 11
Brewerton Elementary School
Asphalt
3'
Concrete
Garage
To Syrac.
STN. 12.
NORTH SYRACUSE, N.Y.
N Syracuse Baptist Church
Open Bible
SANDRA LANE
HY 11
Wason Public School
4 paces
To Syracuse
STN. 13.
SYRACUSE N.Y.
Hwy. 11
Driveway
10'
School
Nettleton Shoe Co.
N. State str.
E. Willow street
Church
STN. 14
LAFAYETTE, N.Y.
1955 Base
Side walk
Driveway
Church
Route 11
STN. 15
LAFAYETTE, N.Y.
1954 Base
Highway 20
House
Presb. Church
To Syracuse
Highway 11
STN. 16.

FIG. 4 – Descriptions of stations 2 to 16

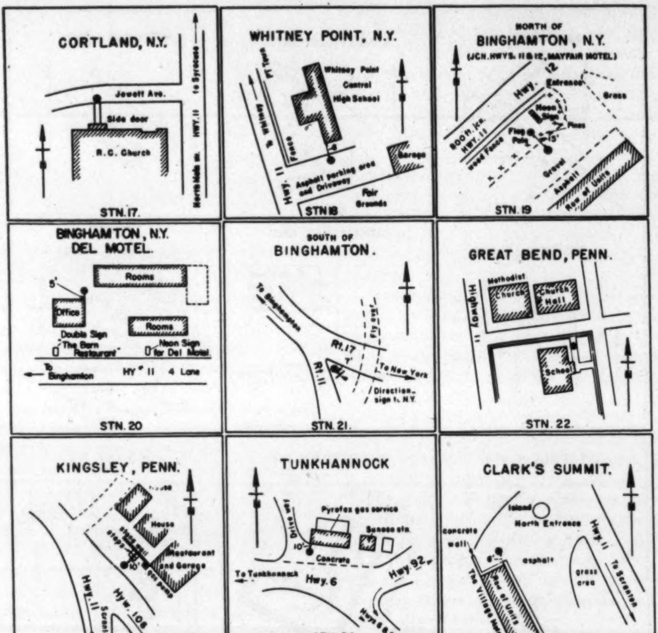
CORTLAND, N.Y.
Jewett Ave.
Side door
R.C. Church
North Main st. HWY. 11 to Syracuse
STN. 17.
WHITNEY POINT, N.Y.
Whitney Point Central High School
To Whitney Point Town
Fence
Hwy. 11
Asphalt parking area and Driveway
Garage
Fair Grounds
STN 18
NORTH OF BINGHAMTON, N.Y.
(JCN. HWYS. 11 & 12, MAYFAIR MOTEL)
Hwy. 12
Entrance
Grass
800 ft. Jcn. HWY. 11
Neon Sign
Pines
Flag Pole
13'
wood Fence
Gravel
Asphalt
Row of Units
STN. 19
BINGHAMTON, N.Y. DEL MOTEL.
5'
Rooms
Office
Rooms
Double Sign "The Barn Restaurant"
Neon Sign for Del Motel
To Binghamton
HY. 11 4 Lane
STN. 20
SOUTH OF BINGHAMTON.
To Binghamton
Fly Rd.
Rt. 17
Rt. 11
7'
To New York
Direction sign to N.Y.
STN. 21.
GREAT BEND, PENN.
Highway 11
Methodist Church
Church Hall
School
STN. 22.
KINGSLEY, PENN.
House
House
steps
Restaurant and Garage
10'
gas pump
Hwy. 11
Hwy. 106
Scranton
STN. 23.
TUNKHANNOCK
Drive way
Pyrofax gas service
Sunoco stn.
10'
Concrete
To Tunkhannock
Hwy. 6
Hwy. 92
Hwys 6 & 92
STN. 24.
CLARK'S SUMMIT.
Island
North Entrance
concrete wall
6'
asphalt
Hwy. 11
grass area
To Scranton
The Village Motel
Row of Units
STN. 25.
PITTSTON
William str.
Hwy. 11
To Scranton
Gas Station
House
Anderson str.
Parking Area
R.C. Church
Lane
STN. 26.
WEST NANTICOKE, PA.
Harter High School
bldg.
excavated
School Yard (Asphalt)
flagpole
wire fence
6'
Iron fence
To HY. 29. (approx. 100 yds)
STN. 27.
SHICKSHINNY
To Scranton
Hill
First Methodist Church
10
HWY 11
STN. 28.
BLOOMSBURG
Hotel Units
Hummel's Motel
10'
HWY. 11
Bloomsburg
Esso service stn.
STN. 29.
SELINSGROVE
1955 on concrete step at back door
St. Pauls Reformed Church
Parking area
back door
10'
Market str.
HWY. 11
To Harrisburg
Parking area
West Mill street
STN. 30.
LIVERPOOL
Liverpool Hotel
Entrance
20'
Old Hwy. 11 (Main street)
trees
New Hwy. 11
Town Park
To Harrisburg
STN. 31.

FIG. 5 – Descriptions of stations 17 to 31

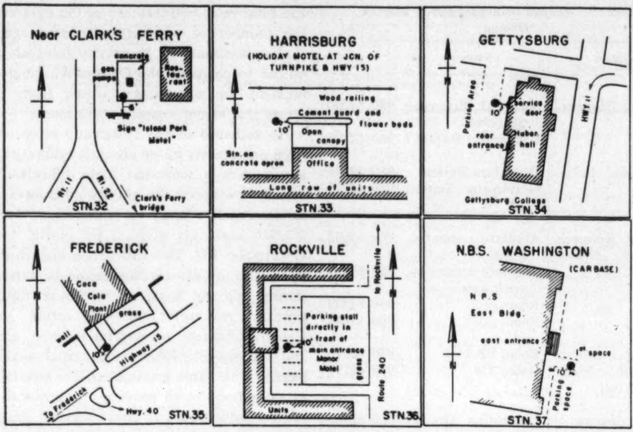
Near CLARK'S FERRY
concrete
gas pumps
Restaurant
Sign "Island Park Motel"
Rt. 11
Rt. 22
Clark's Ferry bridge
STN.32
HARRISBURG
(HOLIDAY MOTEL AT JCN. OF TURNPIKE & HWY 15)
Wood railing
Cement guard and flower beds
10'
Open canopy
Stn. on concrete apron
Office
Long row of units
STN.33.
GETTYSBURG
Parking Area
10'
service door
rear entrance
Huber hall
HWY 11
Gettysburg College
STN.34
FREDERICK
Coca Cola Plant
grass
wall
10'
Highway 15
To Frederick
Hwy. 40
STN.35
ROCKVILLE
to Rockville
Parking stall directly in front of main entrance
10'
Manor Motel
grass
Route 240
Units
STN.36.
N.B.S. WASHINGTON
(CAR BASE)
N P S
East Bldg.
east entrance
1st space
10'
Parking space
STN. 37.
N

FIG. 6 – Descriptions of stations 32 to 37

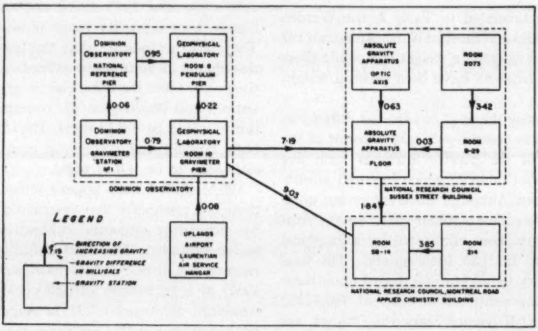
DOMINION OBSERVATORY NATIONAL REFERENCE PIER
0·95
GEOPHYSICAL LABORATORY ROOM 8 PENDULUM PIER
0·06
0·22
DOMINION OBSERVATORY GRAVIMETER STATION Nº1
0·79
GEOPHYSICAL LABORATORY ROOM 10 GRAVIMETER PIER
DOMINION OBSERVATORY
0·08
UPLANDS AIRPORT LAURENTIAN AIR SERVICE HANGAR
7·19
9·03
ABSOLUTE GRAVITY APPARATUS OPTIC AXIS
ROOM 2073
0·63
3·42
ABSOLUTE GRAVITY APPARATUS FLOOR
0·03
ROOM B-29
NATIONAL RESEARCH COUNCIL SUSSEX STREET BUILDING
1·84
ROOM 3B-14
3·85
ROOM 214
NATIONAL RESEARCH COUNCIL, MONTREAL ROAD APPLIED CHEMISTRY BUILDING
LEGEND
7·19
DIRECTION OF INCREASING GRAVITY
GRAVITY DIFFERENCE IN MILLIGALS
GRAVITY STATION

FIG. 7 – Gravity connections in Ottawa

range of the measurements. The standard deviations of a single observation, as determined from the residuals from the mean of repeated measurements, are listed for each instrument. These results indicate that generally the behavior of each gravimeter was much the same throughout all three periods of observation. The Worden instrument, however, may be an exception, as the results of the two 1955 runs have twice the uncertainty of the 1954 measurements. The better quality of the observations and possibly the larger calibration factor obtained for this instrument in 1954 may be related to the fact that the instrument was temperature controlled during the period of these measurements, but not during the later calibrations. A complete analysis of the performance of the gravimeters employed during these measurements is being carried out by R.L.G. Gilbert of the Dominion Observatory and will be reported separately.

On the average the uncertainty of the observations with North American Gravimeter 85 is about twice as great as that of the other two instruments. Therefore in forming the mean grav-

TABLE 1 - *Adopted values for gravity sites in Ottawa*

Location	Station	g
		cm/sec²
Dominion Observatory	National Reference Station	980.62200
	Gravimeter Station 1	980.62194
Geophysical Laboratory	Pendulum Station	980.62295
	Gravimeter Station 1A	980.62273
National Research Council, Sussex Street	Absolute apparatus, floor	980.62992
	Absolute apparatus, optic axis	980.62929
	Room B-29	980.62989
	Room 2073	980.62647
National Research Council, Montreal Road	Room SB-14	980.63176
	Room 214	980.62791
Uplands Airport	Laurentian Airways Hangar	980.62265

ity differences tabulated in Table 2, the Worden gravimeter values and those of North American 137 have each been assigned a weight of 4 while those of North American 85 have been given a weight of 1.

Before adopting the final or adjusted differences in gravity it was necessary to take account of the fact that 24 of the gravity intervals form five closed networks (Table 2) which required adjustment for closure. Although these errors are quite small and have rather a minor effect on the final values, they have been eliminated by a graphical method [*Smith*, 1951] of least squares. The final values of gravity for all stations, based upon these adjusted measurements and a value of 980.62200 for the National Reference Station in Ottawa, are given in Table 3.

Discussion of results—Before comparing these results with those of other investigators it is desirable to estimate the practical limits of error in forming the total Ottawa-Washington difference. In doing this, errors both of the random and systematic variety must be considered.

The random errors, which are believed to be chiefly observational, may be estimated with considerable accuracy from the standard errors of the individual gravity segments. The latter, estimated from the residuals in forming the weighted mean differences (Table 2) are extremely small and in no case exceed 0.02 mgal. Their contribution to the total error will increase as the square root of the number of segments. Assuming, therefore, that a maximum of 36 gravity intervals are required to complete the Ottawa-Washington connection, the uncertainty arising from random errors should not exceed ±0.12 mgal.

An estimate of the systematic error resulting from uncertainty in the absolute calibration of the gravimeters is somewhat more difficult. As previously mentioned the gravity differences depend fundamentally upon a calibration factor of 0.23916 mgal per division for North American Gravimeter 137. This calibration in turn depends upon the results of measurements carried out during July and August of 1955 to strengthen the primary gravimeter network across southern Canada. Aircraft transportation was employed and stations established at principal airports by looping with three gravimeters. The results of this investigation, which provide a provisional datum for the adjustment of most regional gravimeter work completed in Canada, are based upon comparisons against six Cambridge pendulum station values [*Garland*, 1953, 1955], not including Washington, over a gravity range of about 800 mgal. The statistics indicate that the resulting calibration should be accurate to at least one part in four thousand. Over the difference in gravity between Ottawa and Washington the corresponding uncertainty would be ±0.13 mgal. The total error from both random and systematic errors is therefore estimated to be ±0.25 mgal.

While these results appear sufficiently reliable, there is a possibility that systematic errors caused by inaccurate absolute calibration have been under-estimated. The chief difficulty arises from recently published results [*Garland* and *Tanner*, 1957] of a calibration carried out for the North American Gravimeter 137 in August 1954, also by comparison with Cambridge pendulum values in Canada but over a higher range (990 mgal total). This calibration was completed during the latter part of the field season, about two months before the first calibration run (October 1954) was carried out between Ottawa and Washington. The value obtained, 0.24199 ± 0.00012 mgal per division, indicates that the October 1954 calibration (Table 4) should be increased by about 0.13 pct. This would suggest that a value of −502.1 mgal for the Ottawa-Washington difference might be more correct than the one (−501.4 mgal) indicated in the present work. More serious still is the effect that a larger calibration factor would have

TABLE 2 – *Summary of gravity differences in milligals*

Item		October 1954			August 1955			November 1955			Mean differences	
Instrument		North American 137	North American 85	Worden 44	North American 137	North American 85	Worden 44	North American 137	North American 85	Worden 44		
Calibration		0.241671	0.228954	0.110897	0.239160	0.228914	0.110714	0.239053	0.229968	0.111194	Weighted	Adjusted
Weights		4	1	4	4	1	4	4	1	4		
Stations												
	1 to 2	-1.62	-1.65	-1.68	-1.65	-1.69	-1.63	-1.67	-1.71	-1.64	-1.65_2	-1.65_2
	2 to 3	-38.33	-38.17	-38.27	-38.27	-38.30	-38.25	-38.26	-38.32	-38.27	-38.27_4	-38.27_4
	3 to 4	-15.37	-15.57	-15.45	-15.50	-15.48	-15.51	-15.42	-15.45	-15.43	-15.45_3	-15.45_3
Net 1	4 to 5	-20.54	-20.56	-20.51	-20.52	-20.58	-20.57	...	...	...	-20.53_9	-20.53_7
	4 to 6	...	...	...	...	...	...	-20.99	-21.09	-20.95	-20.98_3	-20.98_5
	5 to 7	-26.65	-26.88	-26.70	-26.64	-26.71	-26.68	...	...	...	-26.68_2	-26.68_0
	6 to 7	...	...	...	...	...	...	-26.22	-26.12	-26.27	-26.23_1	-26.23_3
	7 to 8	-7.74	-7.51	-7.69	-7.68	-7.65	-7.73	-7.65	-7.73	-7.67	-7.68_6	-7.68_6
	8 to 9	-51.73	-51.77	-51.63	-51.71	-51.74	-51.65	-51.70	-51.61	-51.59	-51.67_3	-51.67_3
	9 to 10	-32.22	-32.10	-32.17	-32.26	-32.25	-32.16	-32.21	-32.07	-32.25	-32.20_4	-32.20_4
Net 2	10 to 11	-21.26	-21.18	-21.23	...	...	...	...	...	...	-21.23_8	-21.24_4
	10 to 12	...	...	...	-22.31	-22.41	-22.42	...	...	...	-22.37_0	-22.35_1
	10 to 13	...	...	...	...	...	...	-28.03	-28.15	-28.08	-28.06_6	-28.07_9
	11 to 14	-11.89	-11.95	-11.94	...	...	...	...	...	...	-11.91_9	-11.92_5
	12 to 14	...	...	...	-10.81	-10.81	-10.87	...	...	...	-10.83_7	-10.81_8
	13 to 15	...	...	...	...	...	...	-67.52	-67.43	-67.41	-67.46_1	-67.47_4
	14 to 15	...	...	...	-62.47	-62.24	-62.33	...	...	...	-62.38_2	-62.38_4
	14 to 16	-62.74	-62.64	-62.60	...	...	...	...	...	...	-62.66_7	-62.65_2
	15 to 16	...	...	...	-0.26	-0.28	-0.22	...	...	...	-0.24_5	-0.26_3
	15 to 17	...	...	...	-32.33	-32.44	-32.32	-32.37	-32.37	-32.34	-32.34_7	-32.33_9
	16 to 17	-32.03	-32.05	-32.10	...	...	...	...	...	...	-32.06_3	-32.07_1
	17 to 18	-19.80	-19.78	-19.81	-19.78	-19.78	-19.79	-19.71	-19.70	-19.82	-19.78_1	-19.78_1
Net 3	18 to 19	-15.76	-15.87	-15.80	...	...	...	...	...	...	-15.79_0	-15.78_3
	18 to 20	...	...	...	...	...	...	-21.92	-21.82	-21.87	-21.88_7	-21.87_3
	18 to 21	...	...	...	-20.31	-20.17	-20.27	...	...	...	-20.27_7	-20.29_8
	19 to 22	-2.05	-2.06	-2.02	...	...	...	...	...	...	-2.03_8	-2.03_1
	20 to 23	...	...	...	...	...	...	+6.26	+6.26	+6.28	$+6.26_9$	$+6.28_3$
	21 to 23	...	...	...	+4.69	+4.83	+4.75	...	...	...	$+4.73_2$	$+4.70_8$
	22 to 23	+2.20	+2.20	+2.23	...	...	...	...	...	...	$+2.21_3$	$+2.22_3$
	22 to 21	...	...	...	-2.49	-2.54	-2.46	...	...	...	-2.48_2	-2.48_5
Net 4	23 to 24	...	...	...	+4.76	+4.65	+4.79	+4.77	+4.69	+4.71	$+4.74_8$	$+4.74_4$
	23 to 25	-28.08	-28.23	-28.06	...	...	...	...	...	...	-28.08_6	-28.08_4
	24 to 26	...	...	...	-30.45	-30.47	-30.41	...	...	...	-30.43_4	-30.44_7
	24 to 27	...	...	...	...	...	...	-29.22	-29.13	-29.23	-29.21_4	-29.20_5
	25 to 26	+2.43	+2.36	+2.33	...	...	...	...	...	...	$+2.37_8$	$+2.38_2$
	26 to 28	-4.53	-4.33	-4.57	-4.52	-4.51	-4.52	...	...	...	-4.52_2	-4.53_1
	27 to 29	...	...	...	...	...	...	-17.46	-17.59	-17.48	-17.48_3	-17.47_4
	28 to 29	-11.66	-11.72	-11.68	-11.67	-11.68	-11.76	...	...	...	-11.69_3	-11.70_2
	29 to 30	-31.46	-31.50	-31.48	-31.52	-31.52	-31.50	-31.51	-31.52	-31.52	-31.50_0	-31.50_0
Net 5	30 to 31	-20.12	-20.10	-20.13	...	...	...	...	...	...	-20.12_2	-20.10_6
	30 to 32	...	...	...	-30.76	-30.70	-30.79	-30.81	-30.84	-30.78	-30.78_3	-30.79_9
	31 to 33	-45.07	-45.04	-45.10	...	...	...	...	...	...	-45.08_0	-45.09_2
	32 to 31	...	...	...	+10.69	+10.69	+10.76	...	...	...	$+10.72_1$	$+10.69_3$
	32 to 33	...	...	...	-34.37	-34.45	-34.39	-34.42	-34.43	-34.45	-34.41_1	-34.39_9
	33 to 34	-19.64	-19.60	-19.63	-19.66	-19.69	-19.74	-19.59	-19.69	-19.61	-19.64_7	-19.64_7
	34 to 35	+0.36	+0.34	+0.31	+0.34	+0.30	+0.30	+0.34	+0.33	+0.32	$+0.32_8$	$+0.32_8$
	35 to 36	+5.70	+5.82	+5.76	+5.79	+5.77	+5.76	+5.75	+5.80	+5.77	$+5.76_0$	$+5.76_0$
	36 to 37	-12.76	-21.71	-12.75	-12.75	-12.82	-12.71	-12.74	-12.81	-12.64	-12.73_7	-12.73_7

on the results of recent comparisons between the North American and European gravity networks (unpublished work of Morelli, Innes, and Rice). In this investigation it was found that over a range of 700 mgal the European gravity standard and that employed by the Dominion Observatory agree within 0.03 pct. To accept the larger value suggested by the Garland-Tanner investigation

TABLE 3 – *Reference list of adjusted Gravimeter values*

No.	Station	Gravity differences from Ottawa National Reference Station	g
		mgal	cm/sec^2
	Ottawa, Ontario		
	National Reference Pier, Dominion Observatory	0.00	980.62200 (adopted)
	Pendulum Pier, Geophysical Laboratory	+0.95	980.62295
	Laurentian Air Service, Uplands Airport	+0.65	980.62265
	Absolute Gravity Station, N.R.C., apparatus Optic Axis	+7.29	980.62929
1	Gravimeter Station (Dom. Obs.)	−0.06	980.62194
2	Manotick, Ont.	−1.71	980.62029
3	Kemptville, Ont.	−39.99	980.58201
4	Prescott, Ont.	−55.44	980.56656
5	Brockville, Ont. (Court House)	−75.98	980.54602
6	Brockville, Ont. (Church)	−76.42	980.54558
7	Toll Gate, Canada	−102.66	980.51934
8	Toll Gate, U.S.A.	−110.34	980.51166
9	Watertown, N. Y.	−162.02	980.45999
10	Pulaski, N. Y.	−194.22	980.42778
11	Central Square, N. Y.	−215.46	980.40654
12	Brewerton, N. Y.	−216.57	980.40543
13	North Syracuse, N. Y.	−222.30	980.39970
14	Syracuse, N. Y.	−227.39	980.39461
15	Lafayette, N. Y. (1955 stn.)	−289.77	980.33223
16	Lafayette, N. Y. (1954 stn.)	−290.04	980.33196
17	Cortland, N. Y.	−322.11	980.29989
18	Whitney Pt., N. Y.	−341.89	980.28011
19	Binghamton, N. Y. (Mayfair Motel)	−357.68	980.26433
20	Binghamton, N. Y. (Del Motel)	−363.77	980.25824
21	South of Binghamton, N. Y.	−362.19	980.25981
22	Great Bend, Pa.	−359.71	980.26229
23	Kingsley, Pa.	−357.48	980.26452
24	Tunkhannock, Pa.	−352.74	980.26926
25	Clark's Summit, Pa.	−385.57	980.23643
26	Pittston, Pa.	−383.19	980.23882
27	West Nanticoke, Pa.	−381.94	980.24006
28	Shickshinny, Pa.	−387.72	980.23428
29	Bloomsburg, Pa.	−399.42	980.22258
30	Selinsgrove, Pa.	−430.92	980.19108
31	Liverpool, Pa.	−451.02	980.17098
32	Clark's Ferry, Pa.	−461.72	980.16028
33	Harrisburg, Pa.	−496.12	980.12589
34	Gettysburg, Pa.	−515.76	980.10624
35	Frederick, Md.	−515.43	980.10657
36	Rockville, Md.	−509.67	980.11233
	Washington, D. C.		
37	National Bureau of Standards (NBS), Gravimeter Station (car)	−522.41	980.09959
	N.B.S. Sub-basement floor	−520.80	980.10120
	N.B.S. Absolute Stn. Center/apparatus	−521.12	980.10088
	National Reference Pier U.S.C.&G.S., Commerce Building	−501.44	980.12056

would indicate a much larger disagreement (0.15 pct) between the currently adopted standards.

Although no satisfactory explanation can yet be offered to account for the large discrepancy between the independent calibrations obtained in 1954, an investigation is now in progress in an attempt to determine whether it might result from (1) instrumental defects such as non-linearity of scale, change in calibration due to overheating, etc., (2) different observational procedures used during the calibration. (For example, the August 1954 calibration [*Garland* and *Tanner*, 1957] is based upon standard looping procedure south of Edmonton. To the north, however, the results depend on measurements taken at consecutive airports on a single return trip between Edmonton and Whitehorse involving a period of 36 hours. Unpublished results of an investigation by Gilbert show that the two methods of calibration do not necessarily give the same result), (3) inconsistencies in pendulum station values over which the instrument was calibrated. The results of this investigation will be reported separately.

Comparison with the results obtained for the Ottawa-Washington difference by other investigators, while not altogether resolving the difficulty because of disagreement between the various sets of measurements, nevertheless gives considerable assurance that the presently adopted standard is satisfactory. Table 5 summarizes recently published results for this difference obtained with the Cambridge [*Garland*, 1953; *Garland* and *Cook*, 1955] and Gulf [*Woollard* and others, 1956] apparatus. The actual observed differences as well as the corrections used to adjust them to the National Reference sites for easy comparison have been included.

TABLE 4 – *Calibration statistics*[a]

Instrument	Date of calibration	Calibration factor	Number of gravity difference	Standard deviation	Notes
		mgal/div		mgal	
North American 137	Oct. 1954	0.241671±0.000006	27	±0.04	Instrument overheated in June 1955; this calibration based upon Cambridge Pendulum values.
	Aug. 1955	0.239160±0.000055	29	±0.03	
	Nov. 1955	0.239053±0.000006	24	±0.03	
North American 85	Oct. 1954	0.228954±0.000018	27	±0.08	Instrument overhauled in June 1955 and again in September 1955.
	Aug. 1955	0.228914±0.000015	29	±0.06	
	Nov. 1955	0.229968±0.000024	24	±0.06	
Worden 44	Oct. 1954	0.110897±0.000007	27	±0.02	Instrument temperature controlled.
	Aug. 1955	0.110714±0.000007	29	±0.04	Instrument not temperature controlled.
	Nov. 1955	0.111194±0.000008	24	±0.04	Calibration altered during repairs Sep. 1955.

[a] Oct. 1954 measurements observed by L. G. D. Thompson and A. M. Bancroft; Aug. 1955 measurements observed by R. L. G. Gilbert and L. G. D. Thompson; Nov. 1955 measurements observed by J. G. Tanner and R. L. G. Gilbert.

Examination of the table shows that the gravimeter results of this investigation are in excellent agreement with the mean of all the pendulum results (−501.5 mgal). When considered separately it is found that they agree much more favorably with the Gulf pendulum results than with the Cambridge pendulum values. The Gulf pendulum determination differs by only 0.3 mgal, which is about equal to the accuracy estimated for the gravimeter measurements.

The mean value of the Cambridge pendulum determinations is almost in exact agreement with the present gravimeter result. This fact, however, does little towards proving the correctness of the gravimeter results for not only do the separate pendulum determinations seriously disagree with each other (2.9 mgal) but with the gravimeter results as well. The earlier results [*Garland*, 1953] were rejected in a final adjustment [*Garland* and *Cook*, 1955] because of suspected instability in the site of the measurements in Washington. Regarding the latter determinations the present gravimeter result is the greater by 1.4 mgal. This is much too great, and in the opposite direction, to be attributed to calibration uncertainties, and therefore casts doubt on the accuracy of the final determination of the Ottawa-Washington difference using the Cambridge pendulums. This conclusion is supported by recently published results [*Cook*, 1957] of a comprehensive analysis of a large number of Cambridge pendulum measurements. It was shown that the standard deviations of the gravity differences of Ottawa and Washington from Teddington have a standard deviation of about 1 mgal.

In view of the lack of agreement between the various sets of pendulum data there seems little merit at this stage in attempting an overall adjustment in which both pendulum and gravimeter results are incorporated. A more urgent requirement is that more pendulum work be carried out. We therefore look forward with great interest to the results of pendulum work recently completed by L. G. D. Thompson of the Dominion Observatory, using a newly constructed bi-pendulum apparatus [*Thompson*, in press]. New measurements have been carried out not only in Ottawa and Washington but at several intermediate points. When these results are available a complete adjustment will be possible in which all data will be incorporated, not only the work reported here but the results of several other base looping programs carried out over the Ottawa-Washington interval in 1956 and 1957.

Summary and conclusions—The most important contribution of this work is the successful development of a gravity standard for eastern Canada and the United States. The 36 gravity segments which connect the National Reference stations of these two countries have been accurately determined, although some uncertainty still remains in placing the measurements on an absolute basis. The present determination for the difference in gravity between Ottawa and Washington compares favorably, within 0.3 mgal, with recent Gulf pendulum measurements, but disagrees quite seriously with each of the two determinations

TABLE 5 – *Summary of recent connections, Ottawa – Washington*

Reference	Apparatus	Stations connected	Observed difference from Ottawa	Correction to adjust measurement to national reference sites	Measurements referred to national reference sites
			mgal		mgal
Garland, 1953, p. 230	Cambridge pendulum apparatus	National Reference station in Ottawa and Commerce Base in Washington	−502.9	Gravity at both sites of measurement 0.2 mgal greater than at corresponding National Reference Stations	−502.9
Garland and *Cook*, 1955, p. 454	Cambridge pendulum apparatus	National Reference Station in Ottawa and National Bureau of Standards, Washington	−519.64	0.15 mgal to Pier in Ottawa 19.48 mgal to Commerce Base in Washington	−500.00
Woollard and others, 1956, p. 154	Gulf pendulum apparatus	National Reference Station in Ottawa and Geophysical Laboratory, Carnegie Institution of Washington	−520.2 (Weighted Average)	0.2 mgal to National Reference station in Ottawa 18.3 mgal to Commerce Base in Washington [Rose and *Woollard*, 1955, Appendix III]	−501.7
Woollard and others, 1956, p. 154	Gravimeter using Gulf calibration	National Reference Station in Ottawa and Geophysical Laboratory, Carnegie Institution of Washington	−520.3	0.2 mgal to National Reference station in Ottawa 18.3 mgal to Commerce Base in Washington [*Rose* and *Woollard*, 1955, Appendix III]	−501.8
This paper	. . .	National Reference Station in Ottawa and Commerce Base in Washington	−501.4	. . .	−501.4

carried out with the Cambridge apparatus. Pendulum measurements now in progress by the Dominion Observatory are expected to throw further light on this subject.

The internal consistency of the present measurements appears highly satisfactory and this line of stations should serve not only as a satisfactory standard for calibration purposes, but also enable an accurate evaluation of future pendulum determinations. The random error of each gravity difference is estimated to be less than 0.02 mgal which would suggest that over the complete Ottawa-Washington range, 501.4 mgal, the uncertainty is about 0.1 mgal, or one part in five thousand.

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Tropospheric Bending of Radio Waves

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Abstract—A simple and accurate method is presented for computing the refractive bending of radio waves in the lower 100,000 ft of the atmosphere. A given refractive-index profile is approximated by a series of straight lines (layers of constant gradient) and the incremental bending computed for each layer.

The method is applied to the 'standard' atmosphere, and total bending is plotted against the surface refractive index for various vertical angles of arrival from 0 to 1 radian.

Introduction—The bending of radio waves in the troposphere is important in radio astronomy problems, as well as in the precise location by radar of high-altitude aircraft and other targets. Such bending increases rapidly as the angle of arrival approaches grazing incidence, and can amount to a degree or more in many cases. Frequently, it is at these low angles that precise location is most important.

The method described below was developed for computing total tropospheric bending as a function of angle of arrival and refractive-index profile parameters in a simple and rapid way, that retains the accuracy and flexibility of existing techniques. Pearcey [*Pawsey* and others, 1947] developed a simple method for making such computations assuming a linear decrease of refractive index from the surface value to unity at a height of five miles (8 km). Allowance for atmospheric changes was made only by changing the overall gradient. *Schulkin* [1952] describes a method for handling any refractive-index profile by approximating it with a series of straight lines. Thus, the atmosphere is divided into layers, each with a constant refractive-index gradient. The approximation can be made as good as one pleases by using enough layers. His method involves finding an average value for the angle of incidence of the ray in each layer. The numerous computational steps involved, including square roots and averaging, are straightforward, but somewhat tedious.

The method described below uses the same general approach assuming constant-gradient layers, but the procedure is simplified so that each step may be performed graphically, thereby avoiding all computing except simple addition, subtraction and interpolation.

Development of the method—Consider an atmospheric layer of infinitesimal thickness dh (Fig. 1) at height h above the Earth's surface, with a ray passing through the layer at an angle α with the horizontal. If the vertical refractive-index gradient is dn/dh, we can write

$$\begin{aligned} d\alpha &= \frac{dn}{dh}\frac{\cos\alpha}{n}\,(dh/\sin\alpha) \\ &= \frac{dn}{dh}\cot\alpha\,dh \end{aligned} \tag{1}$$

since n differs from unity by at most one part in 2500.

From Snell's law for spherical stratification we have

$$n(a + h)\cos\alpha = n_0 a \cos\alpha_0 \tag{2}$$

where n is the refractive index at height h; a is the radius of the Earth, n_0 and α_0 are the refractive index and the angle of arrival, respectively, at the Earth's surface. Solving (2) for cot α and substituting in (1) gives

$$\begin{aligned} \gamma &= \int_0^h d\alpha \\ &= \int_0^h \frac{dn}{dh}\frac{dh}{\sqrt{\sin^2\alpha_0 - 2(n-1) + 2h/a}} \end{aligned} \tag{3}$$

The atmosphere, as mentioned previously, is assumed to consist of layers, each with a constant refractive index gradient ($dn/dh = k$).

Thus the incremental bending $\Delta\gamma$ for one layer becomes

$$\Delta\gamma = k\int_h^{h+\Delta h}\frac{dh}{\sqrt{\sin^2\alpha_0 - 2h\left(k - \dfrac{1}{a}\right)}} \tag{3}$$

$$= \frac{ka}{1 - ka}\sin(\beta - \alpha_0) \tag{4}$$

where β is the angle at which the ray emerges from the layer (Fig. 2).

Both β and α_0 can be rather large (almost 1600 milliradians for vertical incidence), but their difference is always less than 20 milliradians. Our problem then is to compute this small difference.

If we consider a straight ray emerging from the layer at an angle α (Fig. 2), such a procedure is readily found.

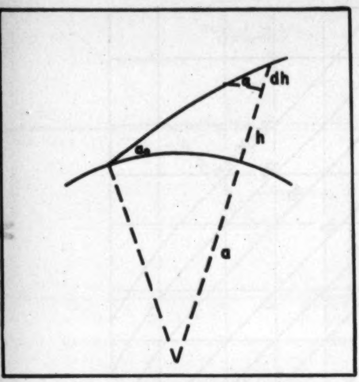

FIG. 1 – Differential ray bending

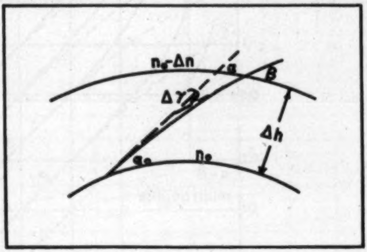

FIG. 2 – Incremental ray bending

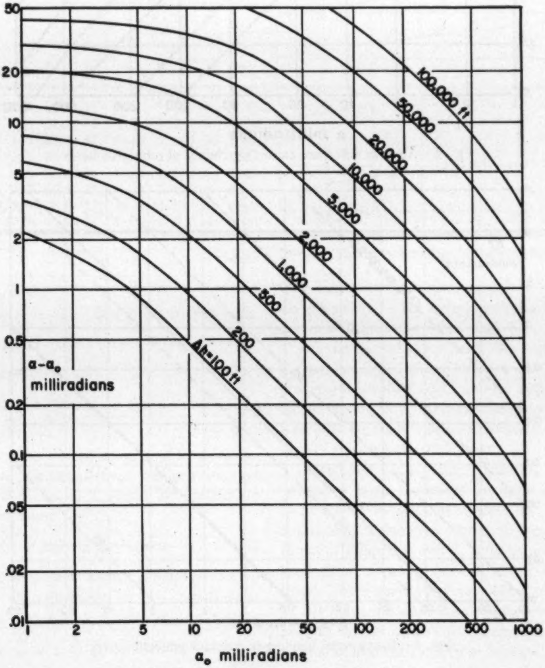

FIG. 3 – Angular difference due to earth curvature

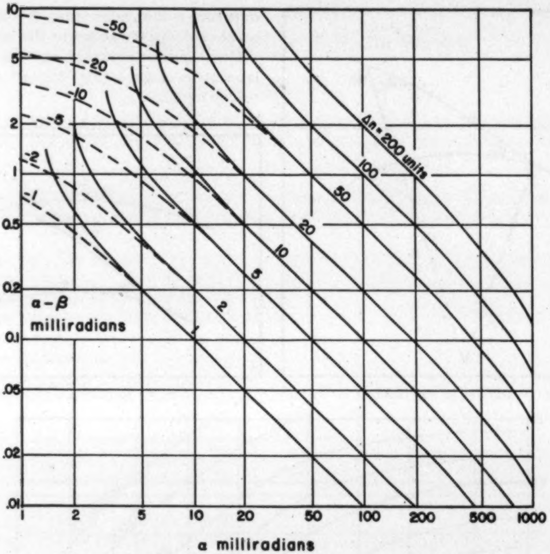

FIG. 4 – Angular difference caused by change of refractive index

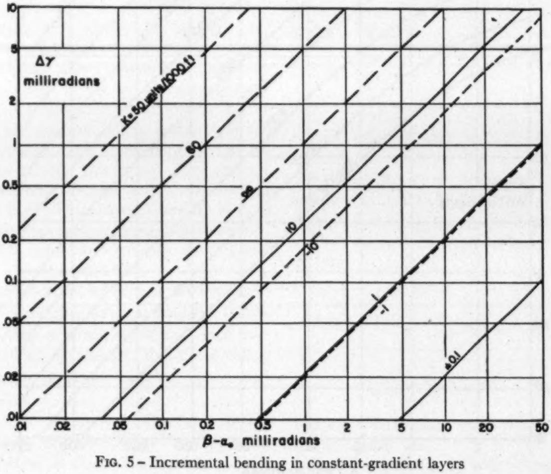

FIG. 5 – Incremental bending in constant-gradient layers

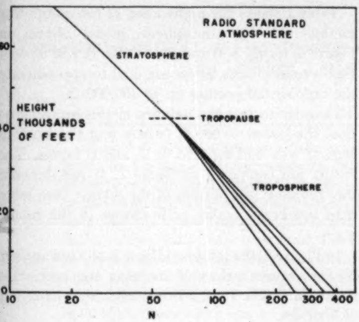

FIG. 6 – Standard atmosphere refractive-index profiles

TABLE 1 – *Sample computation of bending in standard atmosphere*

Height	α_0	$\alpha - \alpha_0$	α	Δn	$\alpha - \beta$	$\beta - \alpha_0$	k	$\Delta\gamma$
ft × 10^3	mr	mr	mr	n	mr	mr	units/ 1000 ft	mr
0–15	0	21.9	21.9	66	3.4	18.5	13.2	7.30
5–10	18.5	10.0	28.5	53	1.9	8.0	10.6	2.30
10–15	26.5	7.8	34.3	42	1.3	6.5	8.4	1.29
15–20	33.0	7.0	40.0	35	0.88	6.1	7.0	1.00
20–30	39.1	10.5	49.6	52	1.07	9.4	5.2	1.07
30–40	48.5	8.8	57.3	34	0.62	8.2	3.4	0.60
40–50	56.7	7.7	64.4	24	0.35	7.4	2.4	0.36
50–60	64.1	7.9	71.0	15	0.21	6.7	1.5	0.22
60–100	70.8	22.8	93.6	24	0.26	22.5	0.6	0.29
Total. . . . . γ =								14.43

Substituting $n = n_0 - \Delta n$ in (2) we can write

$$(1 - \Delta n)\,(1 + \Delta h/a)\cos\beta = \cos\alpha_0 \tag{5}$$

for the refracted ray, and

$$(1 + \Delta h/a)\cos\alpha = \cos\alpha_0 \tag{6}$$

for the straight ray.

Noting that α is a function only of layer thickness Δh and α_0, we can plot $\alpha - \alpha_0$ as a function of these two variables, as in Figure 3. Substituting (6) into (5) we have

$$(1 - \Delta n)\cos\beta = \cos\alpha. \tag{7}$$

Similarly, β is a function only of Δn and α, and we plot $\alpha - \beta$ as a function of two variables in Figure 4. We now can determine $\beta - \alpha_0$, since

$$\beta - \alpha_0 = (\alpha - \alpha_0) - (\alpha - \beta)$$

TABLE 2 – *Computed bending in the lowest 10,000 ft of a standard atmosphere*

Δh	$\Delta\gamma$	Δh	$\Delta\gamma$	Δh	$\Delta\gamma$
ft × 10^3		ft × 10^3		ft × 10^3	
0–10	8.90	0–5	7.30	0–1	3.50
				1–2	1.33
		5–10	2.30	2–4	1.85
				4–6	1.32
				6–8	1.00
				8–10	0.79
Total γ. . .	8.90 mr		9.60 mr		9.79 mr

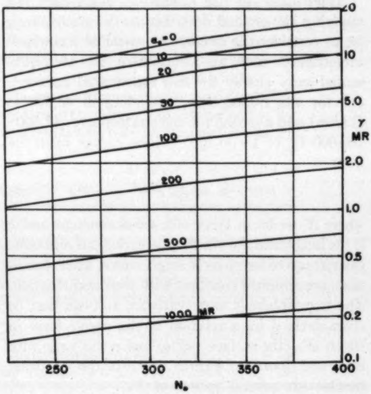

FIG. 7 – Total ray bending in the standard atmosphere

The final step is to solve for $\Delta\gamma$ in terms of $k = \Delta n/\Delta h$ and $(\beta - \alpha_0)$ by representing (4) in graphical form. This is done in Figure 5.

For the second layer, α_0 is the same as β from the bottom layer. Using this new α_0 we repeat the process with values of Δh and Δn applicable to the second layer. After carrying the process to as high a level as we wish, the total bending is simply the sum of the $\Delta\gamma$'s for all layers.

Discussion—In plotting Figure 3, a number of values of layer thickness Δh were used ranging from 100 ft to 100,000 ft (30.5 m to 30.5 km). Interpolation between these curves, as well as those in Figures 4 and 5, is done with a strip of logarithmic paper with cycle length matching the figures. In Figure 4 several values of Δn in units $\times\ 10^{-6}$ are plotted. Positive values refer to the normal case of downward refraction. The dashed curves labeled with negative Δn's are for substandard layers. In this case the ordinate is also negative, that is, β is larger than α. The parameter k in Figure 5 is expressed in terms of a unit representing the increment of n per thousand feet of h. Again, positive k's refer to downward refraction. Negative k's are designated by the short dashes. In this case $\Delta\gamma$'s are also negative. When k exceeds 48 units/1000 ft, the denominator of (4) becomes negative, but $\beta - \alpha_0$ simultaneously becomes negative, hence $\Delta\gamma$ remains positive, as one would expect. The long dash lines refer to this situation when $\beta - \alpha_0$ is taken as negative.

Application to the standard atmosphere—In applying the method described to the atmosphere, let us consider the average or so-called 'standard' atmosphere. Such an atmosphere can be represented very closely by two exponential curves—one for the troposphere, extending to 42,500 ft (13 km) and a second for the stratosphere (42,500–100,000 ft, or 13–30 km). These curves have the form

$$N = N_0 e^{-ch} \tag{8}$$

where $N = (n - 1) \times 10^6$, c is a constant and h is the height. In the stratosphere, one can represent the refractive index by a single curve, since conditions are assumed constant with time and location. The troposphere is more variable, and can best be characterized by a relation of the above form in which N_0 (the surface value) and c will vary with time and location. Figure 6 shows the resulting profiles for several values of N_0.

Table 1 shows the application of the computing method to the atmospheric model shown in Figure 6, for $\alpha_0 = 0$ and $N_0 = 350$. It will be seen that a total of nine layers are used to approximate the exponential profiles up to 100,000 ft.

In order to test the validity of this approximation, the lowest 10,000 ft (where $\frac{3}{4}$ of the bending occurs) was divided into 1, 2, and 6 layers. The results are compared in Table 2. It can be seen that dividing this portion of the column into more than two layers makes little change in the resulting γ.

In Figure 7, the total bending γ is plotted against N_0 for various values of α_0 using the procedure shown in Table 1, and the profile representation of Figure 6.

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Seasonal Changes in Day-to-day Variability of Upper Air Winds Near the 100-km Level of the Atmosphere

E. H. VESTINE

Abstract—The dynamo theory of the magnetic daily variation predicts that winds flowing within the E region at a height of roughly 100 km generate a world-wide electric current system at this level. The electric currents are generated mainly in middle and high latitudes by the horizontal motion of electrically conducting air across the radial component of the geomagnetic field. Near the equator the geomagnetic field is horizontal so that according to the theory the current above the equator must result from an electrostatic field directed from west to east and overhead near noon, closing the current circuit. The theory also implies that this horizontal electric field must extend to the highly rarefied F region, which will be lifted bodily upwards in response to the crossed electric and magnetic field. Hence day-to-day differences in middle latitude winds may be reflected, according to the theory, in day-to-day differences, in heights, and hence in ion-densities of the F region, measured by radio methods.

The day-to-day differences in ionospheric F region critical frequencies near noon are studied as a measure of corresponding differences in the wind-generated ionospheric electric field at the magnetic equator. These changes in F region critical frequencies reflect corresponding changes in height of the F region, caused by the electric field of the daily variation. It is shown that the daily variation, though proportional to both the electric field and the electric conductivity, is probably a good indicator of day-to-day changes in wind speeds in the E region. The data do not support the view that the ionizing solar radiation fluctuates much from one day to the next. This is in accord also with statistical results obtained by Forbush for solar flares and their effects upon the daily variation. The day-to-day changes in wind speed indicated for the E region in middle latitudes are found to be largest in northern winter, and least in northern summer, and are discussed in relation to evidences of variability dependent on season noted from meteorology for tropospheric winds. Changes in wind speed with sunspot cycle are also discussed.

The average magnitude of the daily magnetic variation shows a high correlation with sunspots (as high as 0.99 for yearly averages). Thus, having eliminated electric conductivity of the E region as an important cause of the day-to-day variability in the magnetic variation, the wind speed in the E region must be able to change by a factor of two or more from one day to the next, as a consequence of solar events.

Introduction—In recent years, considerable observational evidence has been accumulating respecting the air flow within the ionosphere [*Briggs* and *Spencer*, 1954; *Mitra*, 1949; *Salzberg* and *Greenstone*, 1951]. These data arise from directly observed motions of meteor trains, noctilucent clouds, and inferences based upon radio wave reflections and scintillations [*Kellogg* and *Schilling*, 1951; *Manning*, *Villard*, and *Peterson*, 1950; *Ryle* and *Hewish*, 1950; *Whipple*, 1954; *Kallmann*, 1955; *Clemmow*, *Johnson*, and *Weekes*, 1955; *Jesse*, 1896; *Störmer*, 1935; *Vestine*, 1934; *Pant*, 1956]. Inferences have also been made on the basis of the dynamo theory of the magnetic daily variations [*Chapman*, 1919; *Vestine*, in press; *Forbush*, 1956; *Maeda*, 1955b; *Kato*, 1956; *Baker* and *Martyn*, 1953; *Martyn*, 1947]. The height of the current layer responsible for the solar daily magnetic variation seems measured to be near and within the E region of the ionosphere, as noted by a magnetometer aboard a rocket [*Singer*, *Maple*, and *Bowen*, 1951]. Similar indications are shown also by height and ion-density measurements of the E region [*Appleton* and *Lyon*, 1957; *Appleton*, 1955]. There now appears little doubt that the magnetic daily variations are due to the dynamo action of winds, in which emf's are produced by the motion of electrically conducting air across the geomagnetic field.

The magnetic daily variation observed at ground level will depend both upon the dynamo electric field and the electric conductivity; if the electric conductivity varies more slowly than do the winds with time, the amplitude of the daily magnetic variation may provide useful indications of the day-to-day fluctuations of the upper air winds in the E region. In particular, it would appear from studies by *Hirono* and *Maeda* [1954], and *Baker* and *Martyn* [1953; also *Martyn*, 1947], that the abnormally large diurnal variation at Huancayo, Peru, on the magnetic equator, is associated with an electric field generated mainly by broadly distributed winds circulating within the E region in middle and high latitudes. Near noon this electric field will have a lifting action upon the F region [*Baker* and *Martyn*, 1953; *Martyn*, 1947]; the day-to-day effects upon F-region height and critical frequency may hence provide a useful indicator of the day-to-day changes in the electric current generating winds flowing in middle latitudes distributed in height near and within the E region. The effects noted for the F region of course will be independent of electric conductivity of the E region as noted near the magnetic equator [*Shimazaki*, 1956; *Sato*, 1956].

It is the purpose of the present paper to provide such estimates of possible day-to-day variability in upper-air winds within the E region using observed data on the magnetic daily variation and height of the F region at the magnetic equator (actually using as indicator the height-sensitive critical frequency of penetration for radio waves). This is done for all days of the years 1938–1945 inclusive, for Huancayo, Peru. The marked seasonal effects noted show changes in kinetic energy which call to mind effects estimated for wind fluctuations in the lower atmosphere by *Mintz* and *Dean* [1952]. Changes in day-to-day wind speeds with sunspot cycle are scarcely detectable, so that it is inferred that the substantial increase in the amplitude of the solar magnetic daily variation with sunspot cycle is probably mainly a gradual electric conductivity effect, together with a general increase in generating wind speed, which appears to be gradual only in successive averages taken over many days. Finally, propagation of meteorological disturbances upwards from the stratosphere is mentioned in relation to the observed day-to-day changes in wind speeds in the E region.

The amplitude of the solar daily magnetic variation S_q—*Bartels* [1946] has listed the daily amplitudes of the solar daily magnetic variation S_q at Huancayo, expressed in terms of a convenient index called δW_2. (The value δW_2 measures the departure from the amplitude of S_q appropriate to an arbitrary sunspot number $R = 50$, chosen thus for statistical convenience; it is hence sometimes positive, sometimes negative. The units of δW_2 are chosen so that the standard deviations for sunspots R and for δW_2 are about 25 each, which makes the appropriate unit for δW_2 about two gammas; one gamma = 10^{-5} cgs.)

The daily measures δW_2 are of special interste because of their high average correlation with sunspot numbers R. Bartels found this correlation factor to be +0.930 for monthly averages, 0.969 by seasonal averages, and +0.988 for annual averages.

In the absence of substantial fluctuations in electric conductivity, δW_2 may provide an effective indicator of upper-air winds which are highly correlated on an average with sunspots.

The change in δW_2 with season—In the present paper the day-to-day differences in δW_2 defined as $\Delta\delta W_2$, say, are of special interest in relation to similar differences in noon critical frequencies for the F_2 region. The day-to-day change may be written $\Delta\delta W_{2,S} = 0.4\omega_1(A_S - A_{S-1})$ for the Sth day in a sequence, where ω_1 is a number used by Bartels to adjust for seasonal changes, and A_S the difference between the field in horizontal magnetic intensity at Huancayo averaged for some hours near and at noon, and for some hours near and at midnight. The respective monthly values of ω_1 used by Bartels in the sequence beginning with January were: 1.04, 0.90, 0.82, 1.13, 1.43, 1.36, 1.79, 1.30, 1.02, 0.88, 0.94, and 1.00. It will be seen that ω_1 is a monthly parameter designed to standardize values for each month. It varies from 1.79 for July to 0.82 in March, for the years considered by Bartels. Hence these numbers of Bartels designed to measure solar wave radiation may also be used in the study of terrestrial seasonal effects. In the case of noon values of f_0F_2, convenient tabulations for the purpose are provided in the ionospheric publication for Huancayo [*Wells* and *Berkner*, 1947].

Before discussing the magnetic and ionospheric results more fully it may be helpful to consider the present status of the dynamo theory of the magnetic daily variation.

Some details of the dynamo theory of S_q—Although there has been considerable discussion of the atmospheric circulation within the E region, in relation to production of S_q, there remains considerable doubt respecting quite important features of this circulation. The main driving forces are often assumed to be tidal, although suggestions have appeared ascribing to atmospheric heating [*Sen* and *White*, 1955; *White*, 1956; *Siebert*, 1956] effects 20 or more times as great as that of the tides. *Wulf* [1945] has presented other arguments stressing the dominant importance of solar heating. At the present time there does not appear to be any clear cut way of resolving this matter of the relative importance of tidal and heating action. Since the resonant action enhancing the tides is in fact temperature sensitive, it is especially difficult to separate the influence of each causative factor. The day-to-day variability of S_q suggests that there are considerable changes in the wind patterns from one day to the next, so that it may be argued therefore that there appear important differences from one day to the next in the winds, and consequently also either in the heating or tidal effects [*Chapman* and *Bartels*, 1940; *Uyeda*, 1949; *Chapman* and *Stagg*, 1929, 1931].

As *Ota* [1949] has shown from the daily magnetic variations observed at many stations of the year 1932–33, the center of both the northern and southern current vortex of the overhead current system for S_q shifts in latitude with month of the year. He showed also that these changes were of the order of about ten degrees latitude with month and season, and that they were different in America, Europe, and the Far East. He also found similar differences existed from day-to-day in extension of earlier studies of *Hasegawa* [1936].

According to the dynamo theory, these day-to-day differences in current system could arise either from daily changes in the upper-air circulation, or changes from day to day in the distribution of ions and electrons throughout the E region. In order to examine this more closely suppose E at any point is the horizontal electric field driving the current system, and that it comprises a dynamo electric field E_i and an electrostatic field E_s (*Chapman*, 1919; *Vestine*, in press; *Forbush*, 1956; *Chapman* and *Bartels*, 1940]. Then

$$\left.\begin{aligned} E_x &= E_{sx} + E_{ix} \\ E_y &= E_{sy} + E_{iy} \end{aligned}\right\} \qquad (1)$$

where x, y indicate components directed to the south and east, respectively.

If S is the electrostatic potential and u, v are the southward- and eastward-directed winds

$$\left.\begin{aligned} E_x &= -\partial S/a\partial\theta + vH_z \\ E_y &= -\partial S/a \sin\theta\partial\lambda - uH_z \end{aligned}\right\} \qquad (2)$$

where $H_z = -C\cos\theta$ is the vertical component of the terrestrial centered dipole. If ϕ is the velocity potential, $u = -\partial\phi/a\partial\theta$, $v = -\partial\phi/a\sin\theta\partial\lambda$ so that (2) may be written

$$\left.\begin{aligned} aE_x &= -\partial S/\partial\theta + C\cot\theta\partial\phi/\partial\lambda \\ aE_y &= -\partial S/\sin\theta\partial\lambda - C\cos\theta\partial\phi/\partial\lambda \end{aligned}\right\} \qquad (3)$$

hence eliminating S

$$\begin{aligned} &\cot\theta\frac{\partial^2\phi}{\partial\lambda^2} + \frac{\partial}{\partial\theta}\left(\sin\theta\cos\theta\frac{\partial\phi}{\partial\theta}\right) \\ &\qquad = \frac{a}{c}\left\{\frac{\partial E_x}{\partial\lambda} - \frac{\partial}{\partial\theta}(E_y\sin\theta)\right\} = F(\theta,\lambda) \end{aligned} \qquad (4)$$

If ϕ comprises typical surface harmonics

$$\phi_n^m = (k_{n,a}^m \cos m\lambda + k_{n,b}^m \sin m\lambda)\, P_n^m(\cos\theta)$$

where $P_n^m(\cos\theta)$ is the normalized spherical function of Schmidt, and λ the local time. Then the left hand side of (4) becomes

$$\sin\theta\,(k_{n,a}^m \cos m\lambda + k_{n,b}^m \sin m\lambda)\, G_n^m(\theta)$$

where

$$\begin{aligned} G_n^m(\theta) = &-\frac{1}{2n+1} \\ &\{[(n+1)^2 - 1][(n+1)^2 - m^2]^{\frac{1}{2}} P_{n+1}^m \\ &\qquad + [n^2 - 1][n^2 - m^2]^{\frac{1}{2}} P_{n-1}^m \end{aligned} \qquad (5)$$

The right-hand side of (4) is also expressible in surface harmonics, and is derived from the total electric field E. This electric field can be derived approximately from the magnetic field at ground level taking the horizontal part of this as $2\pi i$, where i is the current crossing unit width as a part of the current-system overhead. *Maeda* [1955a, 1956] has used such values $i = \sigma E$ where σ is the integrated electric conductivity, σ being estimated taking zenith angle of the sun as ionizing source into account. He derived the first three Fourier terms of the variation of E_x and E_y with latitude and obtained the spherical harmonic coefficients of Φ listed in Table 1, listed according to their order m and degree n.

It is clear that the main term is diurnal, and that next in (about equal) importance are the terms in P_2^2 and P_3^2.

The corresponding result for the distribution of the wind velocity and total electric field is shown in Figures 1 and 2, respectively. Actually, the suggested amplitude of the diurnally varying wind component is about 30 m/sec, the semi-diurnal part being about 10 m/sec, in low latitudes. These results will be useful later in a statistical study.

The electrostatic field which serves to close the current circuit, as estimated by Maeda, is mapped in Figure 3. This electrostatic field extends also to the F region, since there will be some horizontal separation of charge in the E region, and yields a vertical drift velocity at the F region of $W = (E_y/F) \cos I$ where I is the magnetic dip angle, F the total magnetic intensity, and E_y the eastward directed electrostatic field. Taking $F = 0.27$, the change in height dh per second may be written approximately as $dh = (E_y/0.27) \cos t\, dt = 0.13\, E_y \cos (2\pi t/24)\, dt$, where t is measured in hours. The change Δh in height from 06h to 12h is then found on integration to be $0.13\, E_y$.

TABLE 1 – *Maeda's spherical harmonic coefficients of* $\Phi(\theta, \lambda) = \sum_n \sum_m (k^m_{n,a} \cos m\lambda + k^m_{n,b} \sin m\lambda) P^m_n(\cos \theta)$

m	n	$k^m_{n,a}$*	$k^m_{n,b}$*
1	1	−157.6	−152.3
	3	−16.9	5.9
	5	−1.1	−8.5
	7	−1.2	−1.1
2	2	34.5	27.3
	4	9.2	−0.8
	6	−2.3	−2.6
	8	−2.1	−1.4
3	3	−28.2	−20.0
	5	7.4	5.8
	7	2.1	−0.9
	9	−0.5	−0.5

* *Unit 10^{10} cm²/sec*

The observed average increment in height for years of various sunspot number R from 06h to 12h is available from tables of the results of observations at Huancayo. Table 2 lists the average increments for the 6-hour period for h', the virtual height of reflection for radio waves. Also included are values for h_m, the estimated height of maximum electron density, for various years.

Since observed values of A_S (the range in S_q) were not available for 1948, values for all years are calculated from the approximate relationship derived for earlier years, namely, $A_S = 64 + 0.64\, R$. On the other hand the value $A_S \sim 2\pi i = 2\pi k E_y$, where k is the effective electric conductivity, so that having estimated E_y from height data the value k for the various sunspot averages R can be estimated. The results are shown also in Table 2, where the increase in k with R is expressible approximately as $k = 0.012 + 3.1 \times 10^{-5}R$, provided the dynamo electric field is zero or negligible at Huancayo, and that only the electrostatic field contribution is effective. If this is true, the increase in k from 0.013 to 0.017 from 1942–44 to 1948 is about 30 pct for a change in R from 19 to 141. This is less than the 50 pct increase obtained from critical frequencies for this range in R, based upon observed data at the equinoctial months. This discrepancy is substantial, but might possibly be reduced if more refined estimates of actual heights were available. At any

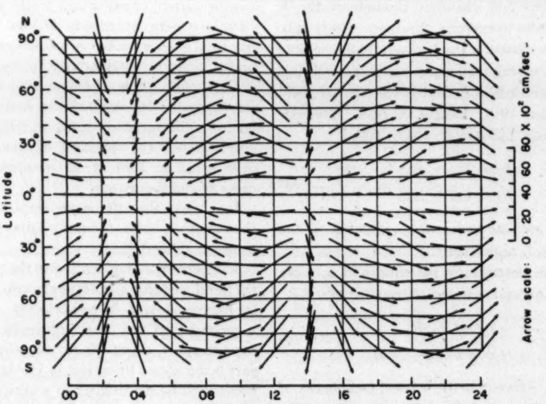

FIG. 1 – Distribution of the total wind velocity

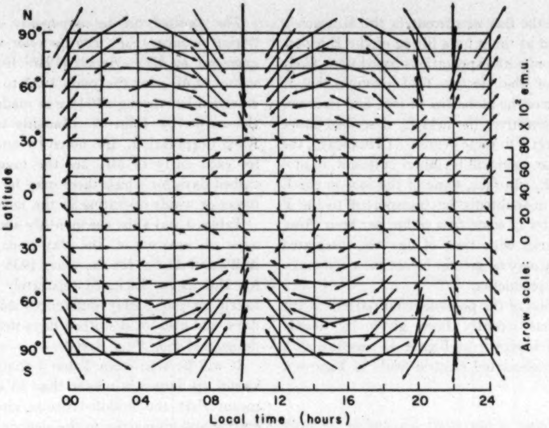

FIG. 2 – Distribution of the total electric field

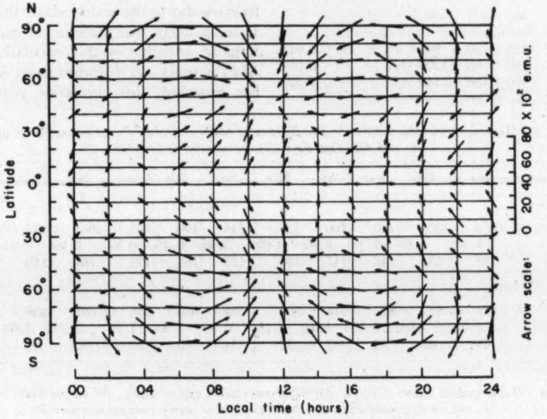

FIG. 3 – Distribution of the electrostatic field

rate it would appear that both the average wind speed and the electric conductivity increased from 1942 to 1948, the former by roughly about 50 pct, and the integrated conductivity by about 30 pct, the net effect providing an estimated increase in S_q amplitude roughly by the factor $1.3 \times 1.5 = 1.95$ at Huancayo from 1942 to 1948, if our assumptions are correct. F-region heating, however, may also increase Δh. As noted in Table 2 the average change from day to day in conductivity actually may be very small.

The total or integrated conductivity k, which appeared to increase with sunspot number, such that $k = 0.012 + 3.1 \times 10^{-5} R$, will probably be affected by the electrostatic field E_y. Appleton [*Appleton* and *Lyon*, 1957; *Appleton*, 1955] has shown that the flow of current in the E region is accompanied at times by a lifting of the E region, in good accord with expectations based upon likely directions of the electric field driving the S_q currents. Since the mobilities of ions and electrons are height sensitive, the field E_y described above will also affect k to some degree. At Huancayo, the E region near noon will be raised in height, in proportion to E_y. In fact, some of the ions in the E region will undoubtedly be transported to the F region at rates of some tens of km per hour. Also, since E_y varies with time of day the integrated conductivity may be greater before the noon maximum of ion production.

A derivation of the possible wind pattern in the E region has recently been given by *Maeda* [1955b] and is shown in Figure 1, together with the total or associated electric fields in Figures 2 and 3.

TABLE 2 – *Values of increments Δh_m and $\Delta h'$ in height in km, and calculated values E_y, A_S, and k in cgs units*

Year	R	Δh_m	$\Delta h'$	E_y	A_S	k
1942–44	19	125	50	960	76×10^{-5}	0.013
1940	67	150	90	1200	107	0.014
1948	141	190	150	1460	155	0.017

The observed average day-to-day change in the critical frequency f_0F_2 with the solar wave radiation expressed by δW_2—Bartels [1946] listed the daily values of δW_2 for the years 1922 to 1937, but an extended list through 1945 was made available to the writer by John W. Mauchly of Remington Rand Corporation. Also noted by notations p or P for each entry of δW_2 are the magnetically disturbed days for which there may be other electric forces or winds operating in the ionosphere.

Tables 3 and 4 list the monthly and yearly averages of squares of the day-to-day differences $\Delta\delta W_2$ and Δf_0F_2, for the years 1938–45, inclusive, for Huancayo. Included separately are averages taken for day-to-day differences $\Delta\delta W_2$ for quiet days, and also for disturbed days defined as those designated p or P by Bartels.

It will be seen from Table 3 that the monthly values are larger in winter than in summer. This means that the middle-latitude circulation generating and giving rise to the electric field directed west-east near noon above Huancayo varies more from one day to the next in winter than in summer. It seems likely that there is not much change in form or intensity of this circulation comparing Δf_0F_2 on quiet and disturbed days. As *Wulf* [1945] has remarked, this circulation pattern may be

TABLE 3 – *Mean squared values of day-to-day differences $\Delta\delta W_2$ and of Δf_0F_2 for magnetically quiet days (A) and disturbed days (B), by months, 1938–1945*

Item	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
(A)												
$\Delta\delta W_2$	1036	1208	760	760	529	546	396	841	1065	683	710	764
Δf_0F_2	1.84	1.89	1.22	0.80	0.69	0.50	0.40	0.84	0.99	0.94	1.78	1.76
No. of days	161	153	146	147	186	170	164	171	161	150	140	140
(B)												
$\Delta\delta W_2$	517	923	803	414	504	1304	676	676	695	408	332	302
Δf_0F_2	1.96	3.05	2.12	2.04	1.18	0.90	1.33	1.28	2.37	2.04	2.09	1.35
No. of days	63	49	62	52	32	34	36	50	50	61	51	47

TABLE 4 – *Mean squared values of day-to-day differences $\Delta\delta W_2$ and of Δf_0F_2, for magnetically quiet days (A), and for disturbed days (B), 1938–1945; also yearly sunspot numbers R*

Item	1938	1939	1940	1941	1942	1943	1944	1945
(A)								
$\Delta\delta W_2$	1008	1119	696	592	760	760	604	649
Δf_0F_2	1.28	1.51	1.14	1.18	1.06	1.01	0.87	0.88
No. of days	219	230	246	235	227	268	251	213
(B)								
$\Delta\delta W_2$	536	538	944	1209	347	182	317	283
Δf_0F_2	1.71	2.06	2.57	2.14	1.51	1.24	1.51	1.60
No. of days	123	106	88	82	66	50	28	44
R	108	89	68	48	1	15	9	32

TABLE 5 – *Average ratios of $\Delta f_0F_2/\Delta\delta W_2$ (1) for p and P days, and also (2) for all other days in Mc/unit of W_2*

Item	1938	1939	1940	1941	1942	1943	1944	1945
R	108	89	68	48	31	16	9	32
(1)	−0.020	−0.023	−0.028	−0.038	−0.034	−0.055	−0.056	0.028
(2)	−0.024	−0.026	−0.030	−0.029	−0.025	−0.024	−0.028	0.023
r	−0.97	−0.81	−0.96	−0.94	−0.94	−0.97	−0.94	−0.98
y at $x = +2.0$	−87	−89	−77	−67	−70	−84	−84	−82
	−93	−133	−83	−77	−80	−89	−96	−85
y at $x = -2.0$	81	76	80	61	73	78	88	82
	87	113	87	69	82	83	98	85

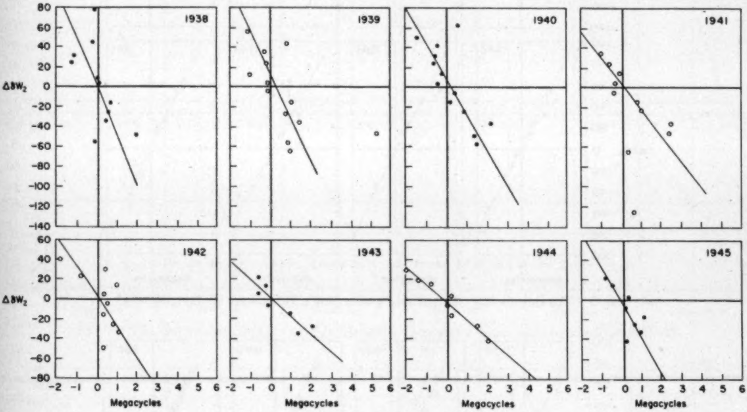

FIG. 4 – The day-to-day changes Δf_0F_2 in the height-sensitive critical frequency, with the magnetic measure $\Delta\delta W_2$, Huancayo, disturbed days, 1938–45

one superposed upon a zonal circulation, which he also suggests may afford a means of explaining the 11h maximum in S_q.

The irregular features shown for $\Delta\delta W_2$ on disturbed days partially reflect other influences, such as additional electric fields [*Baker* and *Martyn*, 1953; *Martyn*, 1947].

Day-to-day changes in wind speed in various years of the sunspot cycle—It is well known that both the magnetic daily variation, upon which δW_2 is based, and f_0F_2, fluctuate more or less in unison with the sunspot cycle [*Chapman* and *Bartels*, 1940]. In fact, both δW_2 and f_0F_2 tend to increase with sunspot number, although we have noted above that increased positive values of the day-to-day differences in Δw_2 are on an average accompanied by larger negative differences Δf_0F_2.

It is also of interest to see whether or not the day-to-day variability of f_0F_2 and δW_2, as measured by the mean of the squares of day-to-day differences in these quantities, varies with the year of the sunspot cycle. Squares of Δf_0F_2 were derived for each of the years 1938–1945, inclusive. It will be seen from the Table 4 that there is little evidence of a substantial change in day-to-day differences in the values with sunspot numbers R for various years of the sunspot cycle. This is in accord with previous findings of *Chapman* and *Stagg* [1929, 1931], who showed that the variability was about the same in S_q at sunspot minimum at equatorial stations such as Batavia and Mauritius. It is interesting also to note that their results indicate that the daily variation in the north component of S_q shows larger day-to-day differences in amplitude in northern winter at both Batavia and Mauritius, as was noted here

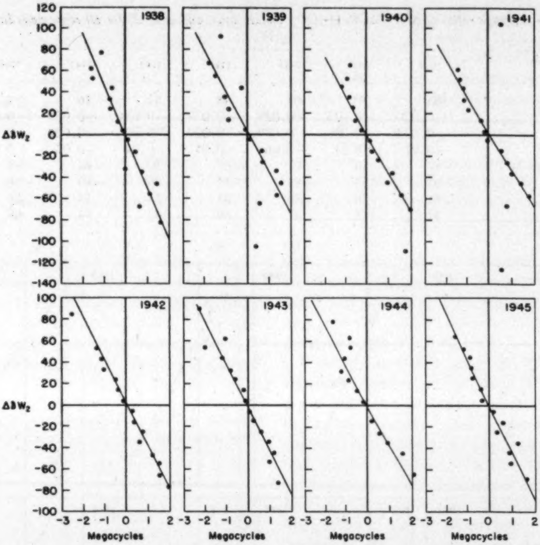

FIG. 5 – The day-to-day changes Δf_0F_2 with $\Delta\delta W_2$, Huancayo, all days, 1938–45

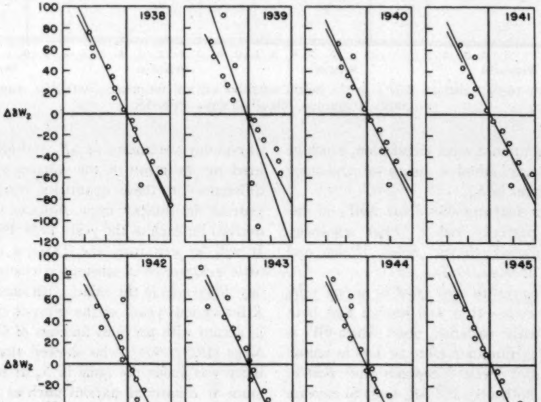

FIG. 6 – The day-to-day changes Δf_0F_2 with $\Delta\delta W_2$, Huancayo, quiet days, 1938–45

for Huancayo, also an equatorial station, reduced here for another series of years. Unfortunately, the day-to-day differences in f_0F_2 have not been available at these equatorial stations for the period of the present study.

The day-to-day magnetic and ionospheric effects interpreted in terms of the dynamo theory and winds near the 100-km level—The wind patterns at 60 to 100 km height with which we are concerned evidently can change considerably from one day to

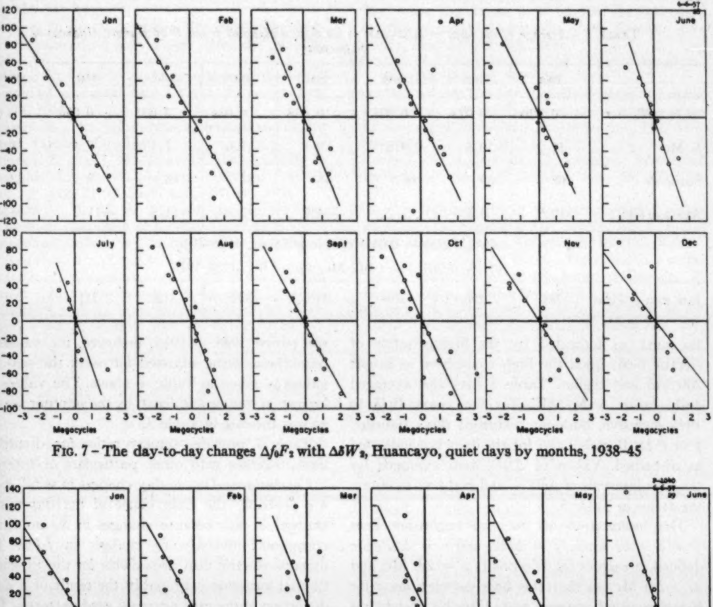

FIG. 7 – The day-to-day changes Δf_0F_2 with $\Delta\delta W_2$, Huancayo, quiet days by months, 1938–45

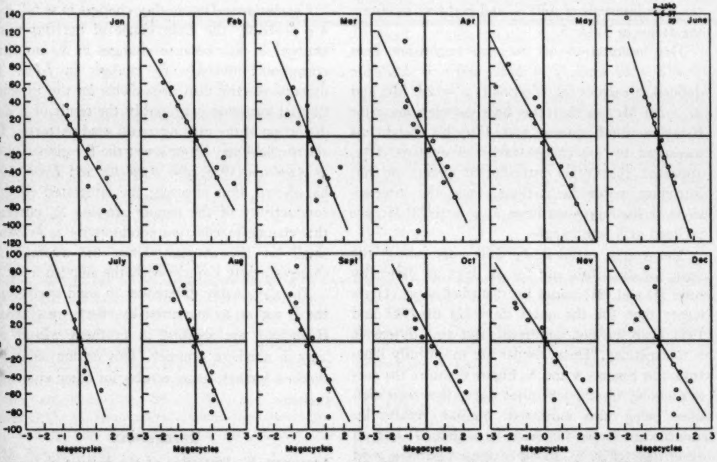

FIG. 8 – The day-to-day changes Δf_0F_2 with $\Delta\delta W_2$, Huancayo, all days, by months, 1938–45

Table 6 – *Values of the ratio* — $\Delta f_0F_2/\Delta\delta W_2$ *by months, Huancayo, 1938–1946 for all days and quiet days*

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
All days	0.030	0.028	0.020	0.022	0.025	0.016	0.018	0.020	0.025	0.026	0.031	0.030
	(0.031	0.025	0.016	0.025	0.036	0.022	0.032	0.026	0.025	0.023	0.029	0.030)
Quiet days	0.030	0.029	0.020	0.017	0.017	0.012	0.013	0.019	0.027	0.022	0.031	0.038
	(0.031	0.026	0.016	0.019	0.024	0.016	0.023	0.025	0.028	0.019	0.029	0.038)

Table 7 – *Average of the ratio* — $\Delta f_0F_2/\Delta W_2$, *for days designated p and P by Bartels, Huancayo, 1938–1945*

	1938	1939	1940	1941	1942	1943	1944	1945
$\Delta f_0F_2/\Delta W_2$	0.020	0.023	0.028	0.038	0.034	0.055	0.056	0.028
f_c Mc	11.2	10.8	9.8	8.8	7.6	7.1	7.1	8.0
Sunspots	108	89	68	48	31	16	9	32
Average δW_2	10.9	8.8	1.2	−4.0	−7.3	−11.6	−11.2	−5.1
$df_0F_2/d(SS) = 0.04$ Mc/unit of SS no., 1938–1946								
$d(f_0F_2)/\delta(dW_2) = 0.012$ Mc/unit of W_2, 1938–1946								
Jan. min *ht* F_2*km*	287	296	308	315	322	312	311	310

the next, as indicated by the lifting action of electric fields upon the high ionosphere at height 200 km and higher. Table 5 lists the averaged daily ratios $\Delta f_0F_2/\Delta\delta W_2$ for the years 1938 to 1945 inclusive, both for disturbed days (labelled *p* or *P* by Bartels), and for the days not indicated as disturbed. Values of Δf_0F_2 were averaged for ten-unit intervals of $\Delta\delta W_2$, and graphed to obtain the ratios in Table 5.

The intersection of the two regression lines $y = a + bx$ where $y = \Delta\delta W_2$ and $x = \Delta f_0F_2$ are defined at each of the two points $x = 2.0$ Mc, and at -2.0 Mc, so that the high correlations r for E-region wind speeds and F-region height as measured by ion concentration is evident. It is apparent that other interdiurnal effects do not introduce major fluctuations, since the intersections of the regression lines at $x = \pm 2.0$ Mc are inclined at a small angle.

The yearly ratios $\Delta f_0F_2/\Delta\delta W_2$ are about the same for disturbed and for all days as shown by rows (1) and (2); values for disturbed days (1) are larger than for the quiet days (2) of 1943 and 1944 near sunspot minimum, and this difference is unexplained. These results are more fully illustrated in Figures 4 and 5. Figure 6 shows the corresponding results for quiet days, the regression lines being also indicated. Similar results by months are shown for quiet days (Fig. 7) and all other days (Fig. 8). In all of these figures a good linear interrelationship is clearly indicated.

Table 6 shows values averaged by months over the period 1938 to 1946, inclusive, the values in parentheses being adjusted for use of the seasonal values ω_1 given in Table 4 above. The values are largest in winter and least in the summer season, as was the case in Table 3.

Table 7 provides similar ratios for disturbed days, together with other particulars of interest.

Conclusions—Day-to-day changes in wind speed are probably the main cause of the day-to-day changes in S_q, because changes in S_q-amplitude correspond inversely to changes in f_0F_2. The dynamo electric field responsible for the magnetic diurnal variation is probably the result of a daily distortion of the existing zonal wind patterns. This electric field may lift or lower the E region slightly, as *Appleton* [1955; also *Appleton* and *Lyon*, 1957] has shown, thus affecting the integrated effective conductivity of the region carrying S_q currents; this change in effective conductivity is evidently small on the average, since the average f_0F_2 changes nearly linearly with the amplitude of S_q.

The day-to-day differences in wind speeds near the E region, as measured by effects measured at Huancayo, are greatest in northern winter and least in northern summer. This finding should be checked further, using results for other equatorial stations.

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Water Gravity Waves Generated by a Moving Low Pressure Area

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Abstract—Hurricanes (typhoons) have an intense low pressure area which often moves rapidly over the surface of the ocean. The coupled water gravity waves generated by such a moving low pressure area have been studied in a towing tank. It was found that the waves generated in this manner had a phase velocity identical to the velocity of the moving low-pressure area. When the low-pressure area was moving at velocities less than the shallow-water wave velocity $\sqrt{gh}$, the waves were of nearly constant period. The period was that which when considered with the water depth would provide a wave phase velocity identical to velocity of the moving low-pressure area. As the group velocity of water gravity waves is less than the phase velocity the wave groups were formed behind the moving disturbance. If the low-pressure area is considered to be a gust it provides a mechanism for generating 'wind waves' of the period observed in the ocean if the forward speed of the gust is taken as the mean speed of the wind. When the velocity of the moving low-pressure area approached $\sqrt{gh}$ the characteristics of the waves changed (at $\sqrt{gh}$ phase and group velocities become identical in the linear theory). The wave disturbance consisted of a large wave followed by a few smaller waves. After the pressure area movement was stopped, the first wave would move ahead of the tail of the disturbance, the distance between the two phenomena increasing with increasing distance traveled by the waves. For certain combinations of initial conditions several waves were formed with this characteristic. These waves had the appearance of the records on the tide gages at certain locations of the East Coast of the United States during Hurricane Carol (and other hurricanes). A study of Hurricane Carol with respect to its speed of forward movement and the water depth over which it moved showed that it should have generated waves of the type obtained in the laboratory and which were actually recorded.

Introduction—A hurricane (typhoon) is a roughly circular tropical disturbance containing poor weather, heavy rains, an area of very low pressure, and strong counterclockwise (in the northern hemisphere) winds. The pressure in the center is often two to three inches (of mercury) lower than in the surrounding air. Maximum wind often exceeds 100 kn. The speed of advance of a hurricane varies considerably; however, the speed may exceed 30 kn in the more northern latitudes, as can be seen in Table 1 [*U. S. Weather Bureau*, 1957].

There is evidence [*Dunn*, 1951; *Unoki* and *Nakano*, 1955; *Harris*, 1956] that long water gravity waves are associated with some hurricanes. It was suggested by D. Lee Harris of the U. S. Weather Bureau that it might be possible to model the moving pressure area of a hurricane using a suction fan and a towing carriage. A preliminary test showed results which were interesting enough to warrant a more detailed study.

No attempt was made to model exactly the shape of the pressure pattern within a hurricane, nor to include the high winds and the associated wind waves; it was believed that these waves would mask the phenomenon being studied: the coupled wave.

A study of a similar type phenomenon had been made by *Press* and *Oliver* [1955]; they studied the flexural waves induced in a thin plate of aluminum by pressure pulses generated by a spark source. The experimental set-up was such that three phenomena could be studied: (1) the equivalent of a 'ground shot', that is, only flexural waves in the aluminum, (2) a combination ground wave in the aluminum and the wave induced by the air pressure wave traveling along the plate, and (3) only the air pulse-induced flexural wave in the aluminum plate. The last phenomenon was analogous to the study described herein. Press and Oliver found that the induced wave had a period such that the phase velocity associated with this period was the same as the velocity of the air pulse. It was found that the group of waves traveled with the group velocity associated with the measured wave period and that the group consisted primarily of waves of constant period rather than a dispersive group of the type associated with the ground blast waves.

Theory—*Kelvin* [1906] developed a theory for a diffused line pressure source moving over a body of infinitely deep water. *Havelock* [1909, 1922, 1926], working along similar lines, developed the theory for water of any depth, with the same assumptions being made as in the development of the linear theory.

Both Kelvin and Havelock found that the moving pressure source would generate transverse waves with phase velocities equal to the velocity of the moving pressure source. The wave periods would be the period associated with the particular wave velocity and water depth. The group of waves would form to the rear of the disturbance as the group velocity of water gravity waves is less than the phase velocity.

Havelock [1909] studied a diffused line pressure of the following sort

$$p = f(x) = \frac{P}{\pi} \frac{\alpha}{\alpha^2 + x^2}$$

where

$$P = \int_{-\infty}^{\infty} f(x)\, dx = \text{constant}$$

with x being measured in the direction of motion, p being the pressure and α expressing the degree of diffusion (it has the dimension of length, the 'width' of the pressure line and should be small compared with the normal wave dimensions). The amplitude of the waves formed by such a system is given by

$$a = \frac{C \cdot \dfrac{2\pi}{\lambda} P e^{-(2\pi\alpha/\lambda)}}{\left(1 - \dfrac{4\pi h/\lambda}{\sinh 4\pi h/\lambda}\right)}$$

where λ is wave length, h is water depth, and C is a constant (probably $2/\gamma$ where γ is the specific weight of water). The denominator expresses the effect of the difference between group velocity and phase velocity upon the accumulation of energy in the waves.

The relationship between the wave height (twice the wave amplitude a) and the wave velocity has been plotted in Figure 1 for a box two feet long traveling over water 1.06 ft in depth, taking α equal to one-half the length of the box which represents the 'hurricane' in our series of tests. On the same graph the experimental points of wave height versus velocity of the pressure area have been plotted. It is apparent that the solution, which depends upon linear wave theory, becomes invalid as the wave celerity approaches $\sqrt{gh}$ because the wave amplitude becomes very large, violating the assumption of the linear theory.

TABLE 1 – *Average forward speed (knots) of United States hurricanes*[a] *two hours before and after entering the coast, by regions*

Texas 1900–1949	Mid-Gulf 1887–1955	Florida Peninsula	Florida Keys	Atlantic (N. of Fla.—S. of Hatteras) 1893–1955	Atlantic (Cape Hat. and northward) 1893–1955
4	6	6	8	7	16
8	7	6	8	9	18
8	7	7	9	9	22
8	9	8	10	12	23
10	10	8	10	14	24
10	10	8	11	15	29
11	11	10	13	16	30
11	11	10	13	16	33
11	14	10	16	17	40
11	16	11		18	47
12	16	11		21	
13	16	11		22	
14	21	11		26	
15	23	11			
15	25	12			
	28	13			
		13			
		14			
		14			
		17			
Mean 11	14	11	11	16	28

[a] Central pressures below 29.00 inches.

Havelock [1922] developed a more useful theory for a moving diffused pressure point which relates the wave resistance to the ratio of the wave celerity to $\sqrt{gl}$, where l is the radius of the pressure disturbance. Havelock's curves have been reproduced in Figure 2, and although they are not directly applicable to the diffused line source they do indicate the general relationship observed in our tests.

Experimental equipment—The experimental equipment consisted primarily of a suction fan mounted at the top center of a plywood box (bottom side open) mounted beneath a towing carriage on the wave-towing tank (Fig. 3). The box extended to within about an inch of the tank walls and to within about one inch of the water surface. Three box lengths were used: 2, 4, and 6 ft. Some data on the pressures within the boxes are shown in Figure 4.

A number of parallel wire resistance wave meters [*Wiegel*, 1956] were mounted on the structure. These meters were mounted as shown in Figure 5 for the tests in water depths of 1.06, 2.26, 3.08, and 4.07 ft. The meters were mounted in slightly different positions for the tests in water depths of 0.50 and 0.17 ft; in addition, wave meters were

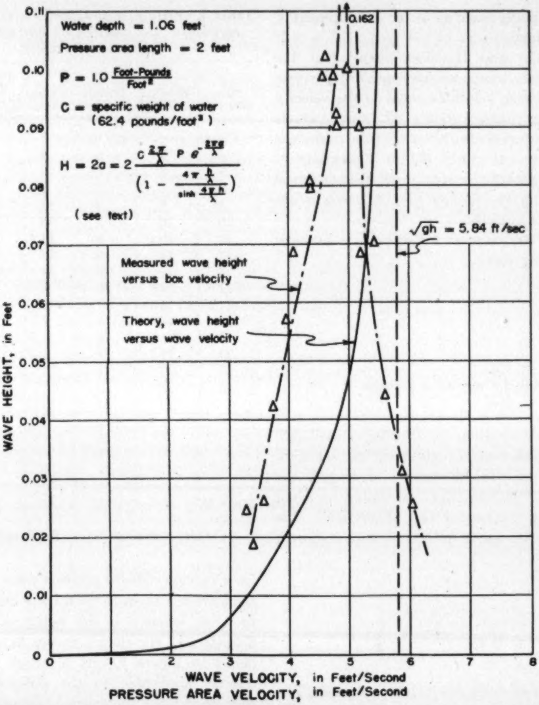

FIG. 1 – Comparison of measured wave height versus pressure area velocity, and theoretical wave height versus wave phase velocity

mounted at each end of the towing tank for the latter tests.

A flood light was installed within the box to light the water surface. A 35-mm Bell and Howell movie camera was installed in the camera pit (at about the center of the tank) to photograph the box and the water gravity waves as they passed the glass wall section of the tank. The camera operation was synchronized with the records from the wave meters by means of an event marker on the Brush penmotor which was used to record the output of the wave meters.

Laboratory procedure—The automatic carriage control unit was set for a chosen carriage speed and the motor was started. As soon as the carriage had come up to its steady speed the fan was started. The water-surface recorders were started prior to starting the fan so that a complete water-surface time history would be available. As the carriage moved past the camera pit, 35-mm moving pictures were taken. A sweep second-hand clock was in the field of vision of the cameras. The starting and stopping of the camera were recorded on the water-surface recorder chart by means of the event marker. When the carriage had run a sufficient distance the carriage and fan were stopped simultaneously. An electric braking system was used so that the carriage could be stopped within a distance of two or three feet. The recorders were left running until the wave system had reflected from the far end of the tank and passed the recording system.

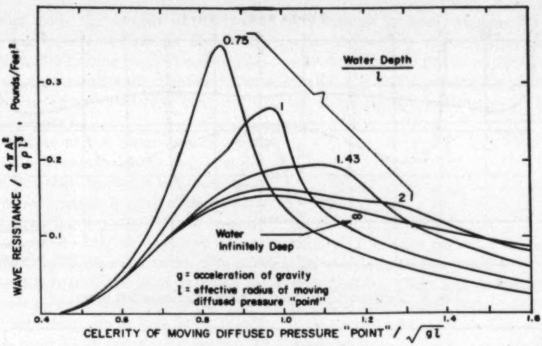

FIG. 2 – Relationship between wave resistance and ratio of celerity of moving diffused pressure 'point' to $\sqrt{gl}$ [after *Havelock*, 1922]

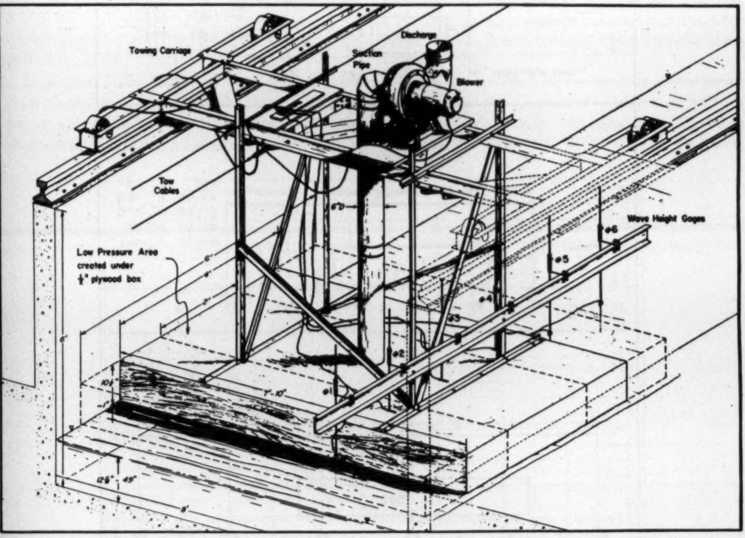
Towing Carriage
Discharge
Suction Pipe
Blower
Tow Cables
Wave Height Gages
Low Pressure Area created under ½" plywood box
6"D
6'
4'
2'
6'
10½"
~1"
7'-10"
12½" - 49"
8'
#1
#2
#3
#4
#5
#6

FIG. 3 – Model hurricane in wave-towing tank

Tests with all three boxes were made with water depths of 4.07, 3.08, 2.66, and 1.06 ft. In addition, tests with the 6-ft box were made with water depths of 0.50 and 0.17 ft.

Results and discussion—One series of tests was run with the fan turned on when the carriage was stationary. The only waves formed by the stationary low-pressure area and the associated 'winds' were of a very small amplitude and length; compared with the waves formed by the moving

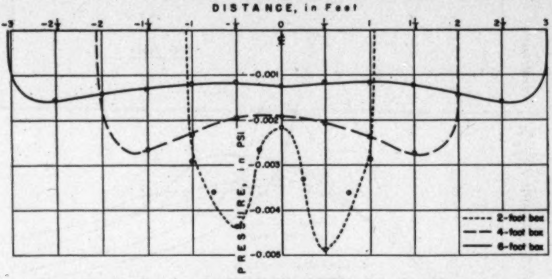

FIG. 4 – Pressure distribution in model hurricane test boxes

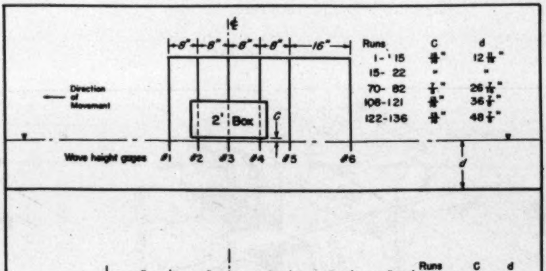
℄
8"
8"
8"
8"
16"
Runs
C
d
1- 15
11/16"
12 11/16"
15- 22
"
"
70- 82
7/8"
26 7/16"
108-121
11/16"
36 7/8"
122-136
11/16"
48 7/8"
Direction of Movement
2' Box
C
Wave height gages
#1
#2
#3
#4
#5
#6
d
16"
16"
16"
16"
16"
Runs
C
d
23- 35
7/8"
12 11/16"
61 - 69
7/8"
27 13/16"
97-107
3/4"
37"
137-152
1"
48 7/8"
4' Box
C
#1
#2
#3
#4
#5
#6
d
Runs
C
d
36- 49
7/8"
12 13/16"
50- 60
15/16"
27 1/8"
83- 95
7/8"
37"
153-171
7/8"
49"
2'
2'
2'
2'
2'
6' Box
C
#1
#2
#3
#4
#5
#6
d

FIG. 5 – Locations of wave meters on model hurricane for experiments in water depths of 1.06, 2.26, 3.08 and 4.07 ft

system they were considered to be 'noise.' The effect of starting and stopping the fan was unnoticeable. Another series of tests consisted of running the carriage without the fan operating. Records taken of the water surface again showed only 'noise.' From the two sets of tests it was evident that the waves discussed in this report were associated only with a moving low-pressure area.

Using the moving pictures taken of the experiments, together with the records of the wave recorders, it was possible to obtain the water-surface profiles under moving boxes. These profiles were not always constant with time; however, their general characteristics with respect to box velocity can be seen in Figure 6.

The main feature of the water gravity waves generated by the pressure area moving over the water surface was that the waves were essentially of constant period, except in very shallow water (Fig. 7). Thus the wave group did not resemble the group associated with an impulsive source. Figure 7 shows the wave trains after they have traveled about 200 ft from the point at which the moving pressure area had been stopped. The wave group was dispersive, as can be seen in the sample records in the right hand side of this figure. The group of waves, where there was a group, traveled with group velocity. As the group velocity is less than its phase velocity for gravity waves the group followed the low pressure area. The phenomenon was similar to that reported by *Press* and *Oliver* [1955].

In Figure 8 the measured wave periods have been plotted as a function of the ratio of the low-pressure area velocity $\sqrt{gh}$ and compared with the theoretical relationship between wave period and velocity for freely running waves. Except for relatively shallow water the period of the waves was such that the phase velocity was the same as the velocity of the moving low pressure area where the phase velocity is given by the set of equations

$$C = \frac{gT}{2\pi}\tanh\frac{2\pi h}{\lambda}$$

$$\lambda = CT$$

where C is phase velocity, g is acceleration of gravity, T is wave period, h is water depth, and λ is wave length computed from $\lambda = (gT^2/2\pi)$ $\tanh(2\pi h/\lambda)$. There was no apparent effect of the length of low-pressure area on the wave velocity.

One trend was evident. The smaller the water depth the greater was the value of $C/\sqrt{gh}$ for which measured values of the forced waves compared closely with theory. When considering relatively shallow water it appears that a forced wave moving with a given velocity has a smaller period than a freely running wave with the same velocity.

When the velocity of the moving low-pressure area was in the immediate vicinity of $\sqrt{gh}$ a different phenomenon was observed. The first wave in the series was of a 'solitary' (actually,

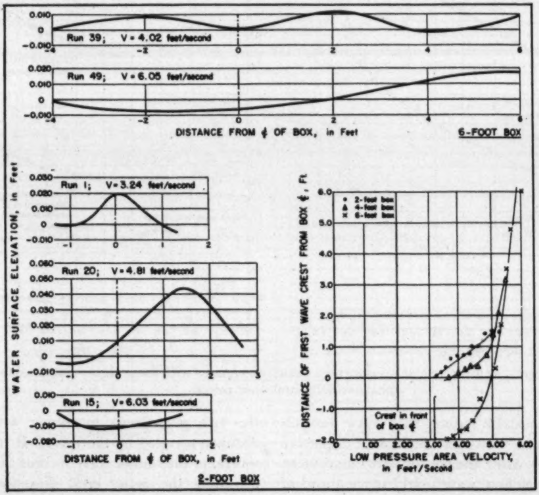

FIG. 6 – Relationships between water surface profiles generated by low-pressure area and velocity of low-pressure area

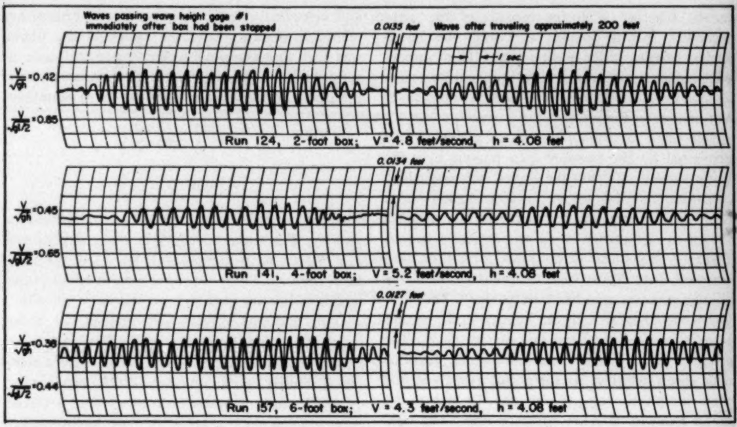

FIG. 7 – Sample records of waves generated by diffused low-pressure area moving with constant velocity over water

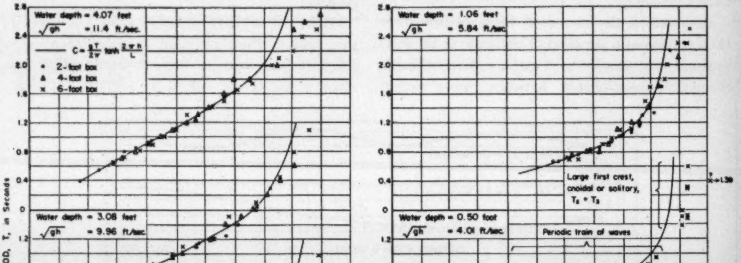

FIG. 8 – Wave period as a function of pressure area velocity compared with linear theory relationship between wave phase velocity and wave period

probably a 'cnoidal') nature; this wave was followed by a series of waves which were dispersive (Fig. 9 and 10). After the pressure area movement was stopped, the first wave would move ahead of the tail of the disturbance, the distance between the two phenomena increasing with increasing distance traveled by the waves. It can be seen in several of the sample wave records that the trough preceding the major crest disappears after the waves have traveled a ways. It appears that this

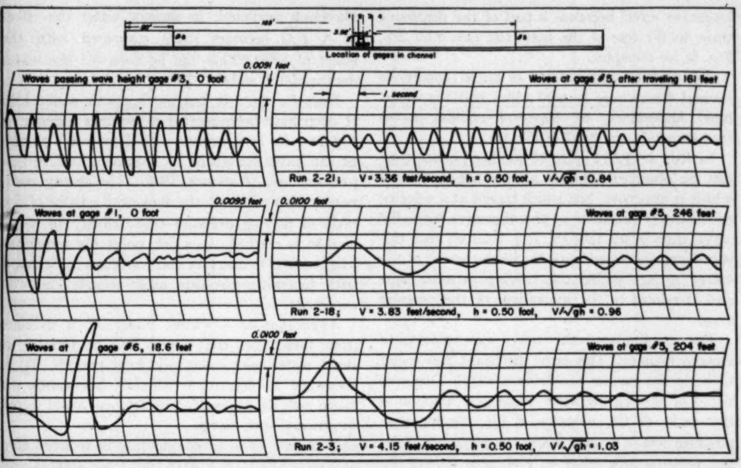

FIG. 9 – Surface-time histories of shallow-water waves generated by the 6-ft low-pressure area for a water depth of 0.50 ft

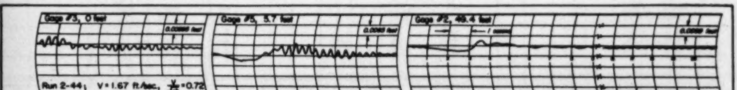

FIG. 10 – Surface-time histories of waves generated by the 6-ft low-pressure area for a water depth of 0.17 ft

'negative wave' becomes a part of the dispersive train to the rear of the first crest (see Run 2–3, Fig. 9, for example).

For certain combinations of initial conditions several waves were formed which had the superficial appearance, at least, of cnoidal waves (see Run 2–34 and 2–37 of Fig. 10).

In Run 2–44 of Figure 10 another phenomenon can be observed. This is a large negative wave which is dispersive, but which travels at a velocity considerably in excess of the dispersive 'periodic' wave train which follows. It is believed that this wave was associated with the displacement of the water surface under the moving pressure area and is related to the dimensions of the pressure area.

The amplitude of the waves were plotted in various manners. The most significant was found to be in the manner of *Havelock* [1922]. This consisted of plotting the wave height as a function of the ratio of the velocity of the moving low-pressure area to $\sqrt{gl/2}$ where l is the length of the low pressure area (that is, 2, 4, or 6 ft; Fig. 2). These data are shown in Figures 11 and 12. As Havelock predicted, in shallow water the effect of $\sqrt{gl/2}$ becomes small compared with the effect of $\sqrt{gh}$. This can be seen for the water depths of 0.50 and 0.17 ft for the 6-ft box.

Data for the 2-ft box moving over water 1.06 ft deep have been plotted in another manner in Figure 1 for comparisons with Havelock's theory of the waves generated by a moving diffuse line pressure area [*Havelock*, 1909]. The theory compares rather well with the data until a value of the ratio of moving pressure area velocity to $\sqrt{gh}$ of 0.86 is reached, at which point the measured height starts to decrease and continues to decrease with increasing pressure area velocity, as was expected.

Application to hurricane waves—It is evident from these tests that waves can be formed in shoal water with relatively long periods. It is necessary to determine whether hurricanes do move with the necessary velocity over shoal water to generate such waves.

In Figure 13 is a reproduction in reduced size of a section of U. S. C&GS Chart No. 1000 (Cape Sable to Cape Hatteras) showing water depths

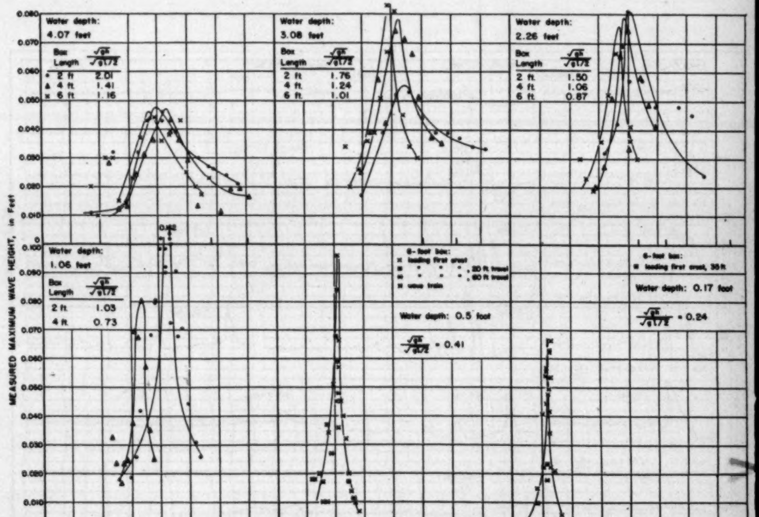

FIG. 11 – Relationship between wave height and $V/\sqrt{gl/2}$

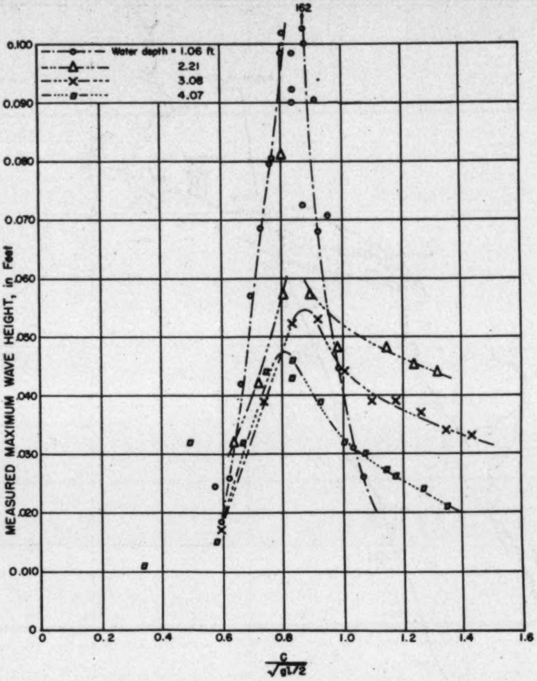

FIG. 12 – Wave height versus $C/\sqrt{gl/2}$ for the 2-ft box and various depths of water

off the East Coast of the U. S. The path of the center of Hurricane Carol is plotted on this chart. It travels over shallow water for an appreciable distance with a forward speed of approximately 30 to 35 kn (between Cape Hatteras and Long Island). The shallow-water wave velocities $\sqrt{gh}$ associated with water depths of 5, 10, 15, 20 and 25 fm are 18.4, 26.1, 31.9, 36.8, and 41.2 kn. It is evident that Carol should have been able to generate the type of long wave that would be known as a surge, especially in the vicinity of Long Island. This result is in agreement with the data presented by *Harris* [1956] which have been shown in Figure 14.

The forward speed of Carol was not usually great for the coastal area north of Cape Hatteras as can be seen from Table 1.

Application to wind-generated waves—The moving low-pressure area which was studied can be considered to be a part of a gust of low pressure in a wind blowing over the surface of deep water. The gust may last only for a minute or so at the air-sea boundary; however, it would be able to generate a train of waves with periods associated with the wave velocity identical to the forward velocity of the gust. Thus the mechanism assumed by *Eckart* [1953] has been shown to raise waves of the periods observed in the ocean. If, as Eckart assumes, the gusts on the average move with the mean wind speed this mechanism would explain the trend of increase of maximum wave period in a spectral analysis of a wave record with increasing wind speed as observed by *Barber* and *Ursell* [1948]. The fact that the speeds of such gusts (being large scale 'turbulence') have a

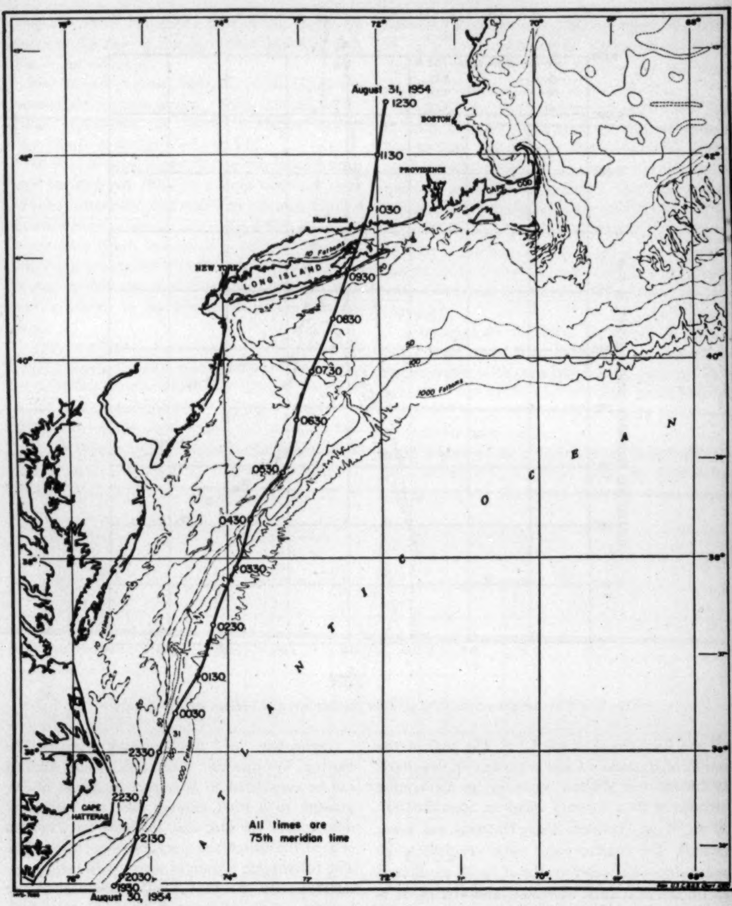
August 31, 1954
1230
1130
1030
0930
0830
0730
0630
0530
0430
0330
0230
0130
0030
2330
2230
2130
2030
1930
August 30, 1954
BOSTON
PROVIDENCE
CAPE COD
New London
NEW YORK
LONG ISLAND
10 Fathoms
50
100
1000 Fathoms
CAPE HATTERAS
A T L A N T I C O C E A N
All times are 75th meridian time
76°
75°
74°
73°
72°
71°
70°
69°
68°
42°
40°
38°
36°

FIG. 13 – Path of center of Hurricane Carol, August 30–31, 1954 [after *Harris*, 1956]

spectrum about the mean value would explain the spectrum of wave periods about a mean value. If the speed of advance of the low-pressure area is plotted as a function of the generated wave period in deep water one gets nearly the identical curve drawn by *Darbyshire* [1952] in his plot of observed maximum wave periods in the ocean versus maximum wind speed.

Conclusions—Water gravity waves, which were not edge waves nor wind waves, were generated by a low-pressure area moving over a water surface in a towing tank.

In the deeper water many of the characteristics, such as wave period, amplitude, and group velocity, could be predicted from a theory presented by *Havelock* [1909, 1922]. If one considers

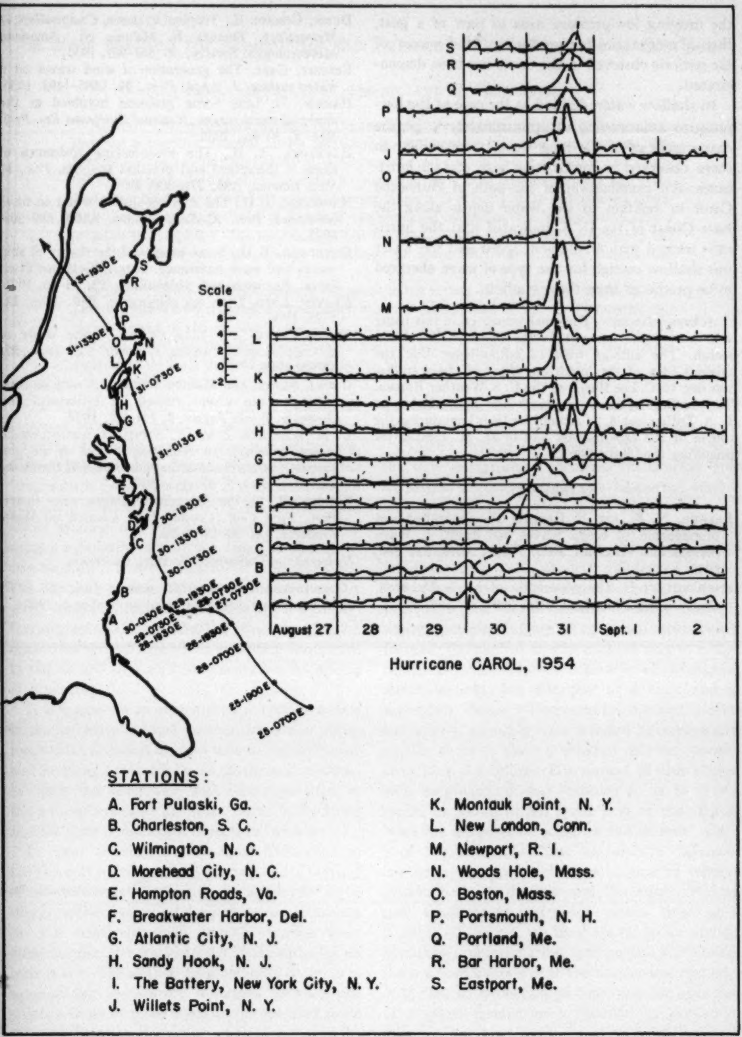

FIG. 14 – Hourly storm-surge height (observed minus predicted sea level), Atlantic coast tide stations, August 27–September 2, 1954 [after *Harris*, 1956]

the moving low-pressure area as part of a gust, then a mechanism for producing 'wind waves' of the periods observed in the ocean has been demonstrated.

In shallow water, defined as the case of the low-pressure area moving at approximately $\sqrt{gh}$, the characteristics of the long waves were similar to those observed in conjunction with certain hurricanes. An examination of the path of Hurricane Carol in relation to the water depth along the East Coast of the U. S. indicated that the hurricane moved with a sufficient speed and the water was shallow enough for the type of wave observed to be predicted from these studies.

Acknowledgments—The work presented in this paper was done under contract to the Office of Naval Research. The authors wish to acknowledge that the original idea of the hurricane phase of these studies was due to C. Lee Harris of the U. S. Weather Bureau. The authors wish to express their appreciation to R. A. Dilley and A. L. Arnold for their help during the course of the experiments, and to M. M. Lincoln for preparing the illustrations.

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A New Method for Measuring the Thermal Microstructure of the Sea

R. J. URICK, L. C. PHARO, AND E. SKUDRZYK

Abstract—Previous measurements of the small-scale temperature structure of the sea have involved a sensitive thermal device carried through the water by a ship or submarine. The present method permits microthermal measurements to be made from a stationary or slowly drifting vessel by means of temperature elements held in a fixed position along a bar. Nine thermistor beads were spaced at varying distances along a 12-ft bar, and the temperature difference between successive pairs of elements was measured by means of a bridge circuit and a sensitive d c amplifier. The records obtained lead to a simple method for determining the correlation function of temperature describing the space distribution of the temperature changes.

A limited number of measurements was made in the waters off Key West, Florida, in conjunction with a field study of the fluctuation of sound transmission in the sea. The spatial and thermal scales of the microstructure are in rough agreement with the Kolmogorov theory of turbulence, and they lead to a prediction for the variability of sound transmission that agrees approximately with the field measurements.

During the past ten or 15 years a number of attempts have been made to obtain some understanding of the fine thermal structure of the sea. *Holter* [1944] at San Diego obtained expanded temperature profiles by using a sensitive thermopile, while *Urick* and *Searfoss* [1948] and *Lieberman* [1951] studied the horizontal microstructure by using a submarine to move a sensitive thermometer through the water. As a result of these studies it is now known that the sea possesses not only a gross thermal structure evidenced by the bathythermograph, but also, like the atmosphere, has a microstructure of dimensions extending downward in size as low as one's instrumentation is capable of measuring.

It is reasonable to attribute observed variations in the intensity of short underwater sound pulses received at distances up to a mile to the scattering and focusing produced by small thermal patches, in much the same way that inhomogeneities in the atmosphere cause air-borne sound to fluctuate and the light from distant objects to twinkle.

In order to relate the observed fluctuation to the thermal microstructure, we required a method of measurement that could be employed by a slowly drifting vessel, and which would give data on the relatively small patches having their greatest effect for wavelengths of the order of an inch or two. The method adopted, essentially, is to measure the temperature difference between two points a short distance apart in the sea, and to do this as a function of spacing so as to measure the thermal and spatial size of the microstructure. The water-borne device consists of a 12-ft bar, bearing thermistor beads at various intervals of separation between one inch and 128 inches.

Figure 1 includes a schematic of the bar, showing the nine temperature elements distributed over its length. In use, the bar was supported from a buoy to avoid the motion of the ship.

Although it is desirable to measure the water temperature at each of the thermistor beads simultaneously, or to observe differences in temperature between each element and a reference element at one end of the bar, simultaneously, it was not practicable from an equipment standpoint. Instead, the method finally adopted was to record the temperature differences between elements, not simultaneously, but one pair at a time and in succession. Figure 1 illustrates the method. Different pairs of elements were selected by means of a switch, so as to place a selected pair in opposite arms of a d c bridge. The output of the bridge, after amplification, was recorded so as to give a record as shown in the lower part of the figure. Note the temperature scale for this sample, which is of 15-sec duration. The temperature difference is observed to vary with time because of relative motion between the bar and the water. Having now temperature difference versus time as a function of spacing, we may appeal to an ergodic hypothesis concerning the temperature statistics of the sea, and assume that the fluctuation statistics of the sea as a function of time, and the statistics at a given instant as a function of horizontal distance, are equivalent. In other words, we will sample the sea by means of the drift of some one or two knots, and obtain the same result as if we

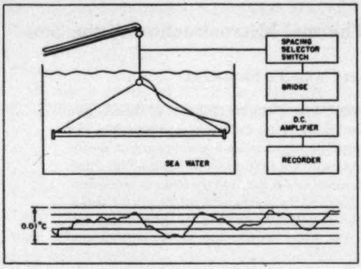

FIG. 1 – Block diagram of the recording equipment, showing a sample record of 15-sec duration

had sampled the sea through simultaneous measurement along the bar for a large number of locations.

Figure 2 is an example of 30-sec records obtained last summer off Key West, Florida, at a depth of 150 ft for the various separations between one and 128 inches. The temperature scale is such that the maximum deviation from the horizontal line on the lowest record is 0.02°C. Note that there is an increasing temperature deviation as the separation is increased. Measurements of this sort were made on several days at a number of depths down to 150 ft, during simultaneous measurements of sound transmission [*Whitmarsh*, *Skudrzyk*, and *Urick*, 1957]. No significant effect of depth was noted, either in the temperature microstructure out to a distance of 128 inches, or in transmission fluctuation. No noticeable difference could be observed between depths in the mixed layer and in the thermocline.

From records like these, temperature deviations were read off, and the mean-square temperature difference was computed and plotted against separation. Figure 3 shows some curves of mean-square temperature, drawn against separation in inches. The vertical scale corresponds to differences of a few thousandths of a degree Celsius. The cross is plotted at the average temperature difference and patch size found by *Urick* and *Searfoss* [1948] in these same waters at shallow depths. The straight line is a line having a slope according to the Kolmogorov theory of turbulence, [*Blokhintsev*, 1946, and *Batchelor*, 1953, chap. 6] which predicts, from dimensional considerations of the equilibrium energy distribution in isotropic homogeneous turbulence, a $\frac{2}{3}$-power law between the spatial and thermal scales of turbulence if the latter is measured in mean-square temperature units.

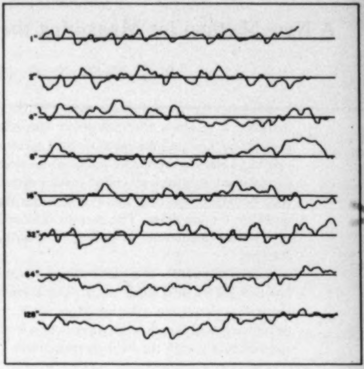

FIG. 2 – Examples of microthermal records showing the temperature difference over a 30-sec interval for various separations along the bar

In conclusion, a few words may be said about the relation between the microthermal data and the measurements made simultaneously on the fluctuation of transmitted sound in the ocean. To relate the two, and to predict the fluctuation from the observed microstructure, we require some sort of theory. A number of such theories are available [*Skudrzyk*, 1957], which all require that we express the microthermal statistics in terms of a temperature correlation function of the Gaussian type; that is, $R(\rho) = \overline{\Delta T(0) \cdot \Delta T(\rho)}/\overline{\Delta T^2} = e^{-a^2\rho^2}$, where $\Delta T(\rho)$ is the temperature deviation from the average at a point distant ρ from the origin at $\rho = 0$, and a is the 'patch size.' It can be shown that the mean square ΔT, except for a constant, is equal to one minus this correlation function, as shown on the left-hand side of Figure 3. However, if we try to represent the measurements by a Gaussian correlation function, we find ourselves in trouble in trying to get a decent fit; in fact, we find that we require more than one such function to agree with the measurements. This is shown by Figure 4, where the plotted circled points are the mean temperature differences as measured at the various spacings, and the dashed and the solid curves are the best that can be done on the basis of assuming one and two patch sizes, respectively. Some measurements of the vertical temperature distribution, obtained with the bar

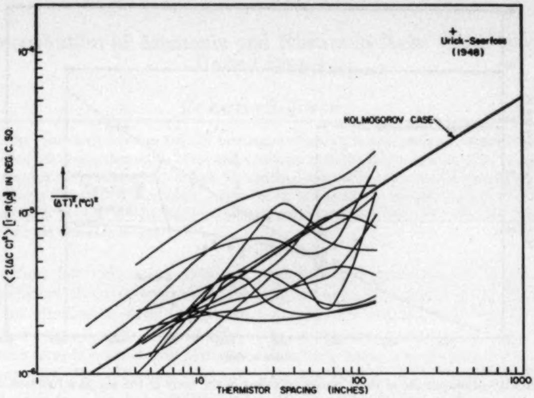

FIG. 3 – Mean-square temperature difference as a function of spacing as measured in different trials during several days

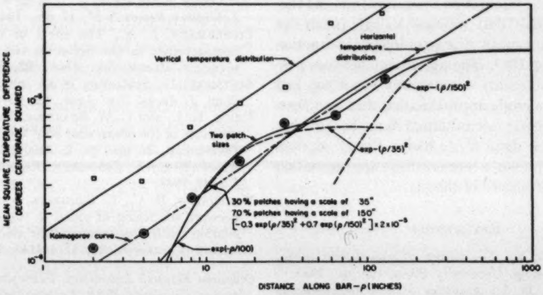

FIG. 4 – Temperature data with attempts to deduce the autocorrelation function of temperature assuming an exponential (exp ρ/a) or a Gaussian [exp $(\rho/a)^2$] correlation function; circled points are averages from the data of Figure 3 with the bar in a horizontal position; the squares show corresponding data points for the bar held vertically

held vertically, are indicated; although the slope is the same as that of the horizontal data, the mean-square temperature difference at the same separation is about three times as great, indicating a lenticular microstructure.

The measurements show that the root mean square temperature deviation increases constantly with the distance between the thermistors. This means that, in a strict sense, a correlation function does not exist. However, over a limited range, the Kolmogorov curve may be well approximated by a simple Gaussian correlation function or a superposition of two such functions corresponding to two different effective patch sizes. An approximation which does not do too badly is illustrated by Figure 5. What is plotted here is the standard deviation of the amplitude of successive transmitted acoustic pulses for different ranges between about 600 and 1400 yd. The crosses and circles show data for two frequencies. The focusing range here refers to the range inside of which focusing and defocusing is the dominant process by which the fluctuation occurs, and beyond which forward scattering of sound plays the dominant role. The

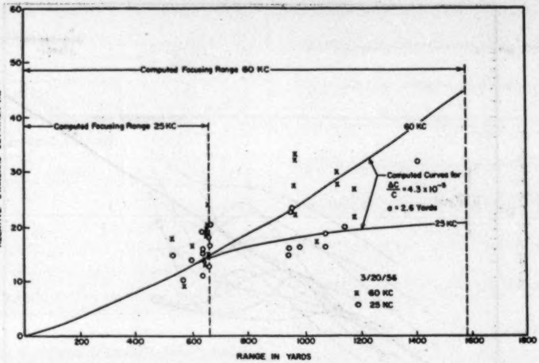

FIG. 5 – Variability of amplitude of short pulses traveling in the body of the sea as a function of distance; each point represents the standard deviation of groups of approximately 50 pulses at a particular range; solid curves show the predicted variability on the assumption of a patch size of 2.6 yards and mean index-of-refraction difference of 4.3×10^{-6}

curves show the fluctuation computed from the theory on the basis that we have a single patch size of 2.6 yd and a mean change of index of refraction $\overline{\Delta c}/c$ of 4.3×10^{-6}. The agreement between prediction and observation apparently is not too bad in spite of the crude approximation that had been made to the basic microthermal data. Presumably more could be done if we had a theory of fluctuation based upon a more realistic approximation to the microstructure of the sea.

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The Distribution of Ammonia and Nitrate in Rain Water over the United States

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Abstract—Quarterly average maps of ammonia and nitrate concentration in rain water over the United States are discussed. These maps indicate that the major sources for both components are near the ground and over land. Comparison with soil maps makes it very likely that the ammonia distribution is primarily controlled by the acidity of the soil. In case of nitrate, no correlation to other geographical parameters could be found, but again, the soil appears to be the most probable source.

Introduction—From July 1955 to July 1956, rain water was collected at about 60 stations in the United States for chemical analysis [*Junge* and *Gustafson*, 1956]. In the specially designed collectors the rain water came in contact with plexiglass and polyethylene only. The collectors were only exposed during rainfall. This was necessary to avoid the influence of dry fallout between the rains which would increase the concentrations in an uncontrolled manner, especially in the dry southwestern areas. The disadvantage of this procedure is that the observers may miss some rain. Because of the randomness, this, however, is likely to have very little influence on the average values.

The samples of each month and station are batched prior to analysis in order to obtain monthly average values. Small amounts of toluene in the sampling bottles protected the samples against activity of micro-organisms. The determination of NH_4 was done colorimetrically by Nessler's reagent, after it was transferred to distilled water by microdistillation to avoid interference with other ions. The determination of NO_3 was also done colorimetrically by adding a chloroform solution of brucine alkaloid and sulfuric acid to the sample. For further details on the network and the sampling procedure, see *Junge* and *Gustafson* [1956 and 1957].

General remarks about the interpretation of rain-water analysis data—The monthly data were currently plotted on maps and checked with respect to the consistency of the concentration pattern. The analysis of apparently inconsistent values was carefully repeated. A few values were considerably higher than the surrounding ones. They were regarded as being contaminated, either by local air pollution or after collection and excluded from further consideration.

It soon became apparent that the monthly concentration maps showed a consistency of certain general features on which fluctuations caused by weather were superimposed. We did not succeed in finding any correlation of the fluctuations with the monthly weather, but it appeared worthwhile to study the consistent pattern by preparing quarterly maps, representing the average concentration weighed with respect to the amount of rainfall. These maps are reproduced in Figures 1 to 8 and will be discussed briefly in this paper.

In a number of samples the NH_4 concentration was below the limit of detection, which was 0.02 mg/liter. In order to obtain the most realistic average data, a concentration of 0.01 mg/l was assigned to these samples. A value of 0.01 mg/l on the NH_4 maps indicates, therefore, that no NH_4 was found during the whole period.

Because of the complexity of rain-water chemistry, the interpretation of these quarterly maps is not easy. To begin with, very little is known about the form in which the compounds enter the rain water; that is, as particulate matter or as gas. Both forms are almost always present. From the few data available [*Junge*, 1956] it appears that the concentration of the gases, NH_3 and NO_2, possibly also some NO, which can form NH_4^+ and NO_3^- in rain water, is considerably higher than the concentration of the corresponding ions NH_4^+ and NO_3^- in the aerosols. The small amount of NO_2^- present in rain water is included in our NO_3^- values. The importance of the gas traces for rain chemistry may, therefore, be much greater than hitherto considered. On the other hand, estimations indicate that the removal of particulate matter by rain may be more efficient. As a very tentative approximation, we can assume that these two facts compensate each other and that gaseous and particulate matter contribute to the rain water content in about equal, but probably varying parts.

Another question is, where the major part of the material is picked up, within the clouds by the cloud droplets, or below the clouds by the falling

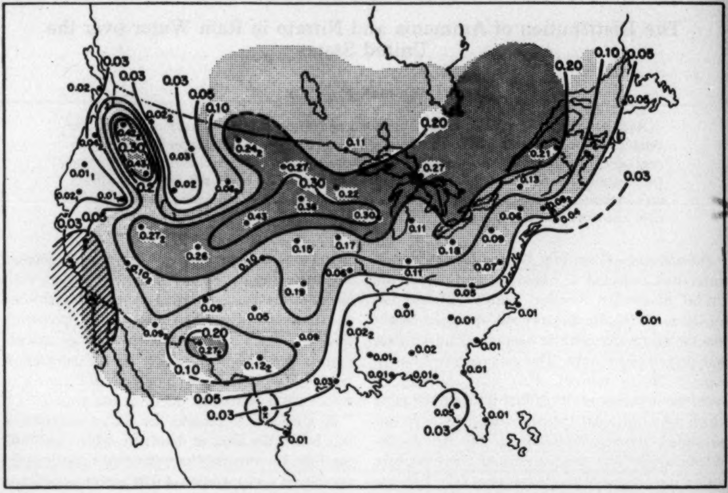
0.03
0.05
0.10
0.20
0.30
0.27
0.43
0.01
0.03

FIG. 1 – NH₄ concentration in milligram per liter; average July–September 1956; the subscripts 1 and 2 mean that samples were available for one or two months only; hatching indicates areas with no samples at all

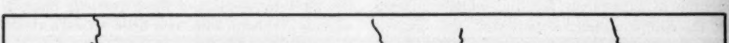
0.03
0.05
0.10
0.20
0.30
0.01
0.03

FIG. 2 – NH₄ concentration mg/l; average October–December 1956

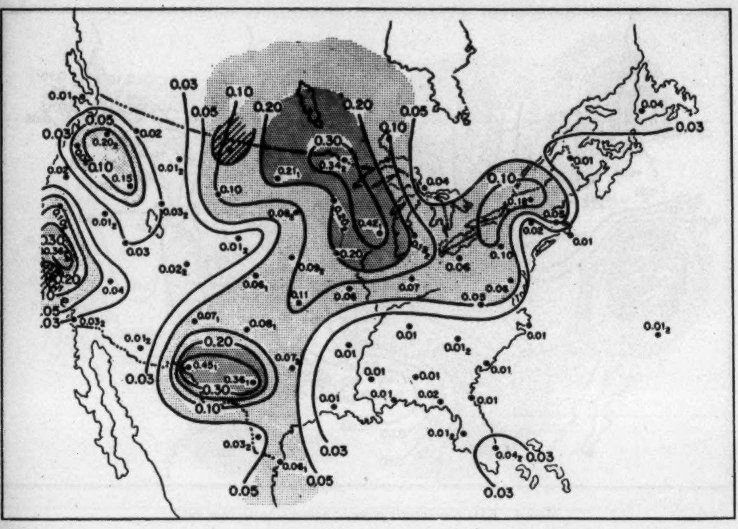

FIG. 3 – NH_4 concentration mg/l; average January–March 1957

raindrops. An estimation of the air volumes involved shows that the first process is the predominant one, if the component is uniformly distributed throughout the troposphere. If the component is, however, concentrated in the layers near the ground, the second process may become more important [*Junge* and *Gustafson*, 1957].

For the interpretation of the pattern on Figures 1 to 8 the following consideration may be helpful: If we assume a component to be uniformly (vertically and horizontally) distributed throughout the troposphere, it is fairly obvious that this should also be true for its concentration in rain water as far as average values over fairly long periods are concerned. There may be higher values in the northern latitudes by a factor of two or so, because of the lower liquid water content of raining clouds as compared with more southern latitudes. But these differences in cloud climatology can only result in very gradual changes over large distances. This theorem of approximately uniform distribution in air and rain could be confirmed in the case of two other components, chloride and strontium 90. Since the ocean is the predominant source of chloride it becomes, on the average, uniformly mixed over the inner part of large continents, resulting in a very uniform distribution of its average concentration in rain water [*Junge* and *Gustafson*, 1957]. Most of the Sr^{90} is stored and accumulated in the stratosphere (probably over years) and constantly released to the troposphere where it is washed out by rain. Sr^{90} can therefore be assumed to have fairly uniform distribution, at least along the same latitude (there is some indication that the transport through the tropopause depends on the latitude) in correspondence with fairly constant Sr^{90} concentrations in rain water (between test periods) within the same latitude range [*Collins* and *Hallden*, 1957].

A look at the maps reveals that the NH_4 and NO_3 concentrations in rain water are far from being uniformly distributed. In general, the values drop near the coast and are low over the ocean, as indicated by the data from the Bermudas, the Azores, and some weatherships (the latter two not indicated in the maps). It further appears that certain geographical areas over the United States show, throughout large parts of the year, consistently low or high concentrations. If we apply the theorem of uniform distribution in air and rain water in a reversed way, it must be concluded that the major sources of fixed nitrogen are not over the

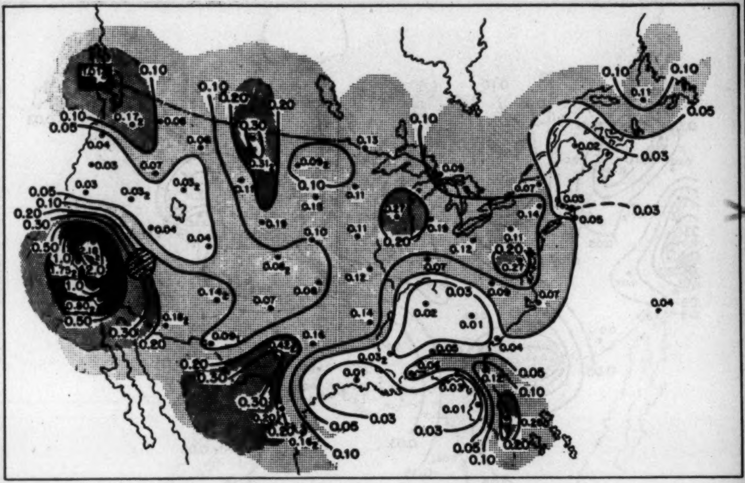
0.10
0.10
0.05
0.10
0.20
0.20
0.30
0.31
0.13
0.10
0.09
0.10
0.10
0.05
0.03
0.05
0.10
0.20
0.30
0.50
1.0
2.0
1.0
0.50
0.30
0.20
0.20
0.30
0.30
0.20
0.05
0.03
0.03
0.05
0.10
0.10
0.20
0.27
0.07
0.03
0.01
0.02
0.04
0.04

Fig. 4 – NH₄ concentration mg/l; average April–June 1957

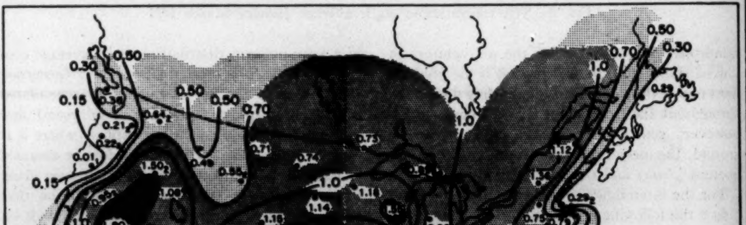
0.50
0.30
0.15
0.50
0.50
0.50
0.70
0.73
1.0
0.70
0.50
0.30
1.0
0.15
0.50
1.0
1.5
1.44
1.14
1.18
1.0
1.12
0.15
0.04
0.10
1.0
0.50
0.70
0.30
0.15
0.13
0.15
0.15

Fig. 5 – NO₃ concentration mg/l; average July–September 1956

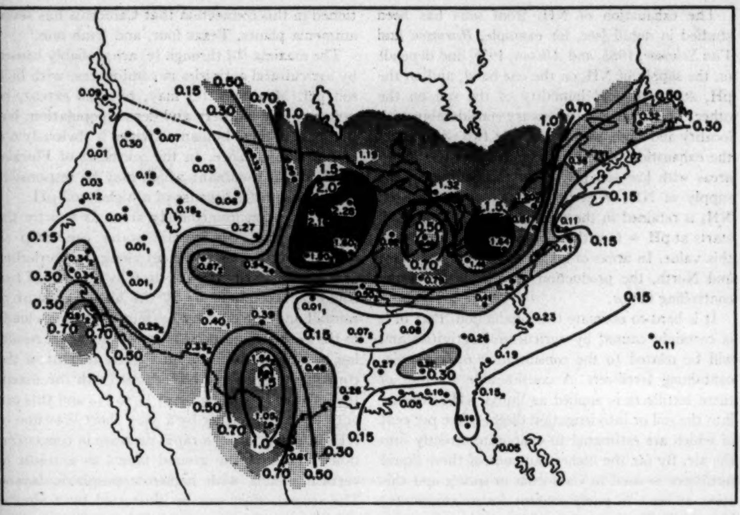

FIG. 6 – NO_3 concentration mg/l; average October–December 1956

ocean, but bound to certain geographical areas over land. This implies that they are very likely to be at or near the ground.

The distribution pattern of NO_3 in rain water excludes the photochemical production of NO_2 in the stratosphere as a possible supply for tropospheric nitrate, as sometimes speculated [*Virtanen*, 1952]. It is also obvious that there is no correlation to thunderstorm activity. This confirms estimations by *Hutchinson* [1954] and others, for example, [*Virtanen*, 1952] that NO_3 formed by lightning can only account for 10 to 20 pct of the observed NO_3 concentrations in rain.

The NH_4 maps—The NH_4 maps, Figures 1 to 4, show the following more or less consistent features:

Maxima tend to appear over (a) California, particularly in the early summer (Fig. 4) where it is confirmed by three exceptionally high values; (b) the Pacific Northwest; (c) New Mexico and northwest Texas; (d) the North Central States (this maximum is very broad and fluctuating); (e) the Northeast (this maximum is weak and not regular, and often part of (d)); and (f) Florida, except in Figure 2 (this maximum is often indicated by one value only and is very weak).

Minima can be distinguished over (g) the whole Southeast (in this area, with the exception of Florida, almost no values reach the limit of detection; this minimum is a regular feature on all monthly maps; in Fig. 2 this minimum does not show up clearly because of the overall low NH_4 level during this period); and (h) the northern Rocky Mountain area, extending farther south in winter.

The comparison with a large variety of maps of geographical parameters, such as density of industry, population, and agricultural activities, did not produce evidence to explain the NH_4 distribution pattern. Finally, the soil maps provided a clue for an understanding. The Southeast is characterized by the yellow reddish laterite soil which is depleted of its alkali content and has a low pH value. Soils of low pH absorb whatever NH_3 may be formed by decomposition of organic material or added by fertilizer. The contours which separate the soils of low pH in the Southeast run closely parallel to the drop of the NH_4 concentration in this area. This decrease in the NH_4 concentration is quite pronounced, often by a factor of ⅛ to ¹⁄₁₀ over a distance of 500 miles.

The exhaustion of NH_3 from soils has been studied in detail [see, for example, *Harmsen* and *Van Schrever*, 1955, and *Allison*, 1955] and depends on the supply of NH_3 on the one hand, and on the pH, structure, and humidity of the soil on the other. The latter two items vary considerably with locality and time, so that the first two will control the exhaustion of NH_3 in a more general way. In areas with low soil pH, as in the Southeast, the supply of NH_3 is of little importance, since all NH_3 is retained in the soil. Loss of NH_3 from soil starts at $pH = 6$, with no observable escape below this value. In areas of alkali soils, as in the West and North, the production of NH_3 becomes the controlling factor.

It is hard to estimate this production. Part of it is certainly caused by agricultural activities and will be related to the consumption of ammonia-containing fertilizers. A considerable fraction of these fertilizers is applied as liquid NH_3, injected into the soil or into irrigation ditches, five per cent of which are estimated to evaporate directly into the air. By far the highest amount of these liquid fertilizers is used in California in spring and this may, at least in part, account for maximum (a) [*Scholl*, *Wallace*, and *Fox*, 1955]. It may be mentioned in this connection that California has seven ammonia plants, Texas four, and Utah one.

The maxima (b) through (e) are probably caused by agricultural activities in combination with high soil pH. Maximum (e) may, to some extent, be influenced by industry and denser population, but the share of these human activities is obviously not of great importance. In the southeast of Florida, coral rock is dominant which may be responsible for maximum (f) because of a higher soil pH.

The question immediately arises as to why the NH_4 concentration in rain water can drop so rapidly and to such an extent along the borderline of the acid laterite soils. A drop by a factor of two could be accounted for by the higher amount of rainfall and liquid water content in raining clouds in the Southeast, especially in summertime, resulting in a higher dilution of a given amount of the constituents. But the NH_4 drops (with the exception of Fig. 2) by a factor of $\frac{1}{5}$ to $\frac{1}{10}$ and this can only be caused either by a very short life-time of NH_3 in the air or by a rapid decrease in concentration of NH_3 in the ground layers as a result of vertical mixing with higher tropospheric layers. The second effect can be illustrated by a similar situation in the case of the chloride distribution.

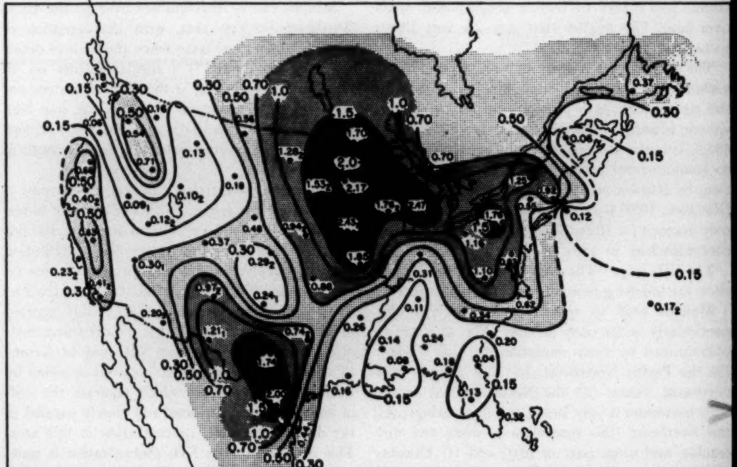
0.15
0.18
0.30
0.15
0.06
0.50
0.16
0.54
0.71
0.13
0.30
0.70
0.50
1.0
0.56
0.66
0.50
0.40_2
0.50
0.63
0.23_2
0.41_2
0.30
0.09_1
0.10_2
0.12_2
0.18
0.48
0.37
0.30
0.30_1
0.29_2
0.37_2
0.24_1
0.20_2
1.21_1
0.74_2
1.74
0.30
0.50
1.0
0.70
2.00
1.5
1.0
0.70
0.60
0.44
0.30
1.5
1.70
1.28_2
2.0
1.53_2
2.17
1.76_2
2.47
2.43
0.94_2
1.85
0.88
0.26
0.16
1.0
0.70
0.70
0.50
1.25
0.92
0.56
1.76
1.5
1.16
0.83
1.10
0.31
0.11
0.62
0.34
0.14
0.24
0.08
0.18
0.15
0.20
0.04
0.15
0.13
0.32
0.37
0.30
0.06
0.15
0.12
0.15
0.17_2

FIG. 7 – NO_3 concentration mg/l; average January–March 1957

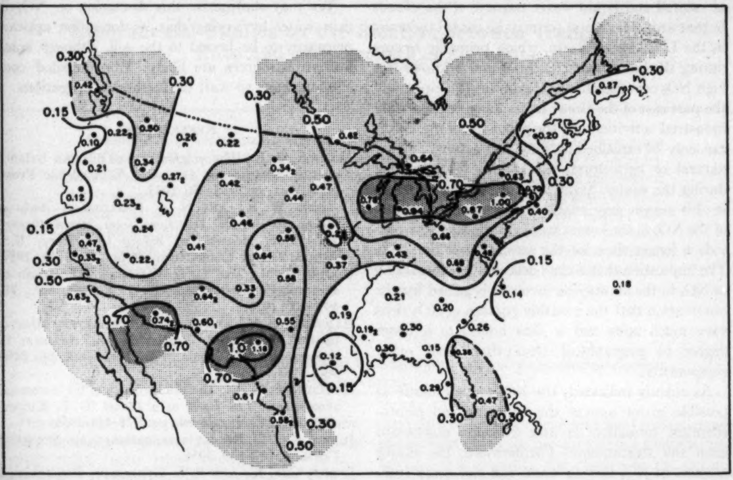
0.30
0.42
0.30
0.30
0.15
0.10
0.22
0.50
0.26
0.22
0.50
0.62
0.50
0.30
0.27
0.21
0.34
0.27
0.42
0.34
0.47
0.64
0.20
0.12
0.23
0.44
0.70
0.63
0.79
0.30
0.15
0.24
0.46
0.56
0.78
0.94
0.87
1.00
0.40
0.47
0.41
0.64
0.35
0.30
0.33
0.22
0.37
0.43
0.66
0.38
0.15
0.50
0.58
0.63
0.64
0.33
0.14
0.18
0.21
0.70
0.74
0.60
0.55
0.20
0.19
0.70
1.0
1.18
0.19
0.30
0.26
0.12
0.30
0.15
0.36
0.70
0.15
0.29
0.61
0.47
0.58
0.30
0.30
0.30
0.50

FIG. 8 – NO_3 concentration mg/l; average April–June 1957

The sources of chloride are the sea-spray particles formed over the ocean. It was shown [*Junge* and *Gustafson*, 1957] that over the oceans and near the coast the majority of sea-spray particles are concentrated in the layers near the surface and are washed out primarily by the falling raindrops below the clouds. As the air masses move inland, the particle concentration in the lower layers where most of the rain is formed is rapidly decreasing by vertical tropospherical mixing. This can result in a decrease of Cl in rain water by a factor of ⅕ to 1/10 over a distance of about 500 miles in agreement with the observations. The estimated decrease of sea spray particles by washout over the same distance is, on the other hand, too small to account for the observed values.

The NH_4 drop towards the southeast across the borderline of acid soils shows similar features as that of Cl along the coasts. The NH_4 values decrease also by a factor of ⅕ to 1/10 over a distance of about 500 miles. It appears reasonable, therefore, to conclude that vertical mixing again is the predominant process. It can be assumed that NH_3 is concentrated in the lowest tropospheric layers over the source areas farther north and west just as the sea spray over the oceans. It may well be that a rapid washout of the NH_3 by rain supports the dilution effect of mixing, but at the present time nothing is known about the lifetime of ammonia in the air.

The maps indicate a seasonal variation of the general NH_3 level with a maximum in late spring and early summer and a minimum in the late fall and early winter.

Discussion of NO_3 maps—The fluctuation in the concentration pattern with the monthly maps of NO_3 concentration, Figures 5 to 8, was more pronounced than with NH_4 and most other chemical constituents. The following features on the quarterly maps seem to have some reality. Maxima tend to appear over (a) the northern part of the United States, often split by the Great Lakes area; (b) the western Texas area, except in Figure 5; and (c) California, and adjacent areas eastwards on some of the maps. Minima tend to appear over (d) the northern Rocky Mountain area; and (e) the Southeast.

In general, some of these features have a similarity with the NH_4 maps, although details do not agree. The minimum in the Southeast is less regular and the difference in concentration against the adjacent area in the West and North is smaller than with NH_4. We think that this NO_3 minimum is largely the result of dilution by the higher rates of rainfall and liquid water content of the clouds in that area. Maximum (c) may be caused by smog in the Los Angeles Basin, which primarily occurs during the late summer and fall and is known for high NO_2 concentrations. Maximum (a), especially the part east of the Great Lakes, may be caused by industrial activities, but the part west of the Lakes can only be explained by some soil activity, either natural or agricultural. Maximum (a) is strong during the winter. Stagnation of stable air masses in this season may enable a higher accumulation of the NO_2 in the lowest tropospheric layers or provide a longer time for the formation of the NO_3. The impression that a time delay for the formation of NO_2 in the air may be involved is gained by the observation that the monthly pattern of NO_3 does vary much more and is thus bound to a lesser degree to geographical areas than most other components.

As already indicated, the NO_3 maps exclude as possible major sources the lightning and photochemical formation in and diffusion downward from the stratosphere. Furthermore, the major amount of NO_3 in rain water can not come from industrial or other human activities because in this case a much closer relationship to industrial areas in the Northeast and elsewhere should be expected. The maps rather point to the earth surface as source. These two possibilities exist:

(1) the NO_2 is formed by oxidation of NH_3. This would explain some similarity with the NH_3 pattern, blurred by a delay due to reaction time.

(2) Along with the considerable amount of N_2O, which is well known to be produced and released by the soil [*Goody* and *Walshaw*, 1953], a small fraction of NO or NO_2 may be formed directly in the soil. According to *Allison* [1955], NO is formed from HNO_2 in acid soils (PH $\leq$ 5), but this does not seem to agree with the soil maps.

We may summarize this discussion on NO_3 in rain water by saying that its formation appears primarily to be bound to the soil, although some industrial sources are likely. More detailed conclusions have to wait for further investigations.

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Experimental Studies on the Relation between Transpiration Rate and Meteorological Elements

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Abstract—Water loss caused by transpiration is significant, especially on a bright summer day. The utilization of precipitation as a water resource will be affected largely by transpiration. Thereupon, the investigation of the transpiration rate was carried out as a fundamental datum of water resources, using a wind tunnel which can maintain any meteorological condition. Various examinations on the potometer method were performed and the method was found satisfactory in our investigations. The transpiration rate obtained by the potometer agreed within ±2.4 pct with that of the potted plant. The following empirical formulas were obtained from the relation of the transpiration rate to radiation intensity and wind velocity for *Myrica rubra*.

$$T = T_0 \mp v/(0.55 \times 10^{-1.87R} \cdot v + 0.32 \times 10^{-2.35R})$$
$$T_0 = (2.09R + 1.67)\, H_d + 35.62R$$

Also, the relations of the leaf temperature to transpiration rate and meteorological elements were studied. Some systematic relations were found.

Introduction—It has already been reported by many investigators, such as *Briggs* and *Shantz* [1916], *Cribbs* [1919, 1921], *Blaydes* [1928], *Meyer* [1932], *Kadota* [1950], *Shapiro* and *DeForest* [1932], and others, that the transpiration rate shows a daily periodicity, and its correlation with meteorological elements has been investigated.

Meyer [1928], *Thornthwaite* and *Holzman* [1942], *Thornthwaite* [1943], and others, have investigated the effect of air temperature on transpiration rate. The trends were represented by linear relations. The gradually accelerating tendency of transpiration rate with increase of air temperature can be seen in the results of laboratory experiment by *Roeser* [1932].

Martin [1943], *Bialoglowski* [1936], and others, have shown the linear relation between transpiration rate and relative humidity.

Martin [1935] investigated the effect of radiation intensity on transpiration rate of *Helianthus annuus* under natural conditions, using shade tents, and found the relation to be linear within the limits of experimental error. As to the effect of wave length of light, *Leclerc du Sablon* [1913] suggested that the accelerating effect of radiation on transpiration rate may be caused partly to heating of the leaves and partly to a change in the permeability of the protoplasm. *Iwanov* and *Thielmann* [1923] have shown that the transpiration rate under blue-violet light is 50 or 60 pct more than that under red-yellow light of the same intensity. *Lepeschkin* [1930] has shown that the permeability of the protoplasm of *Elodea* leaves increases under methylene blue light with increase of the light up to ten per cent of full sunlight, but beyond this intensity the change in the permeability of protoplasm is very little.

Renner [1910], *Seybold* [1929ab, 1930], *Wrenger* [1935], *Wilson* and *Livingston* [1937], *Nakayama* and *Kadota* [1948–9], *Satoo* [1948abcd, 1949ab, 1952, 1953], and others, have investigated the effect of wind velocity on transpiration rate. According to Renner, this effect on *Rhododendron hybridum* was indistinct under the scattered light. Seybold reported that the effect on plants mainly composed of cuticular transpiration was increased by the wind, but on plants mainly composed of stomatal transpiration was small. According to Wrenger's experiments on 38 species in a laboratory, the transpiration rates were raised to their maxima for the species (12 to 150 pct) after 10 or 15 minutes, and then gradually decreased. Nakayama and Kadota reported that the transpiration rate of the Japanese pine decreases or increases by the influence of wind according to clear or cloudy weather, respectively. The lag period of transpiration rate caused by the change of wind velocity was measured on willows by Wilson and Livingston, and on *Cryptomeria japonica* by Satoo.

As noted above, there are many reports on the effects of meteorological elements on transpiration rate. Since these studies were not satisfactory to our present aim, the following experiments were carried out.

Examination of the method for measuring the *transpiration rate*—Various methods have been used to measure the transpiration, such as *Stahl's* [1894] or *Bakke's* [1914] cobalt paper method, the *gasometrische Methode* employed by *Schratz* [1931], and *Minckler* [1936], the weighing method, the potometer method, and others. The weighing method may be one of the most useful for this purpose. Using potted plants, it becomes necessary to expose the plants under constant environmental conditions for a long period in order to take readings, because of the rapid decrease of the sensitivity of balance according to the unavoidable soil weight in the pot, as has already been mentioned by *Stocker* [1929]. Using cut shoots instead of potted plants eliminates the need for the weighing method. From this point of view, the author has adopted the potometer method throughout the investigation, except the weighing method has been employed in comparing the transpiration rates of potted plants with shoots.

Strictly speaking, the potometer method does not give the true transpiring rate, but rather the amount of water absorbed by the cut end of the shoot. Nevertheless, according to *Knight* [1917, 1922], the amount of water absorbed by the cut end almost exactly coincides with the amount of water transpired; wilting will occur with only one per cent decrease of water content in a leaf.

Another difficult problem is the effect of detaching a branch from its parent tree. The theories and experimental results on this problem differ widely in the investigations by *Iwanoff* [1928], *Darwin* and *Pertz* [1911], *Laidlaw* and *Knight* [1916], *Knight* [1922], *Stålfelt* [1929abc, 1932], *Firbas* [1931], *Kamp* [1930], *Schratz* [1931], *Huber* [1927], *Stocker* [1929], *Pisek* and *Cartellieri* [1931, 1932, 1939], *Bosian* [1933], *Kadota* [1950], *Pfleiderer* [1933], and others. It was necessary to examine this problem before carrying out our investigation.

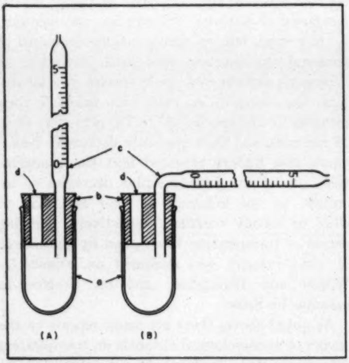

FIG. 1 – Diagram of the potometers used; A, vertical measuring pipette type; B, horizontal measuring pipette type; a, test-tubes; b, rubber stoppers; c, measuring pipettes; d, hole for shoot

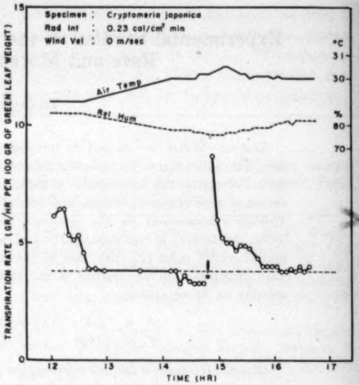

FIG. 2 – Transpiration rate before and after the severance of stem; ! shows the instant of severance; Aug. 13, 1953

Apparatus used—Two types of potometers (Fig. 1) were employed. Figure 1A shows the vertical measuring pipette type potometer, in which the pressure of water column from 8 to 25 cm will be exerted upon the cut end of a shoot. Figure 1B shows the horizontal measuring pipette type potometer, in which nearly constant water pressure is maintained. A potometer is supported by a metal stand.

Comparison of the transpiration rate of shoots with rooted plants—Six *Cryptomeria japonica* two years old and five *Cinnamomum camphora* three years old had been prepared and placed in pots by Miyano nursery in November 1952. Two of the *Cryptomeria japonica* and one of the *Cinnamomum camphora* and two *Diospyros kaki* grown in pots for about one year after planting in 1950, were selected for our purpose. The experiments were carried out in August and September, 1953.

In the experiment, the plotted plant was put in the laboratory the day before in order to allow the soil temperature to approach the room tem-

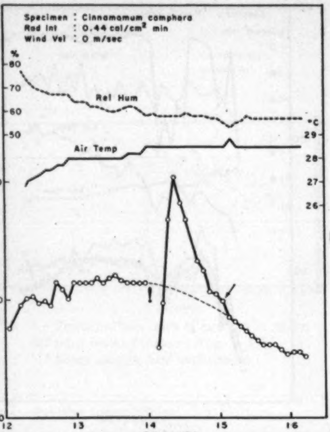

FIG. 3 – Transpiration rate before and after the severance of stem; ! shows the instant of severance; Sep. 18, 1953

perature which was kept as nearly constant as possible. Then, the pot was made water tight and was hung on a precision balance. The sensitivity of the balance was adjusted to ±5 mg. The experiment was carried out under the radiation of eight electric lamps of 500 watts each. Weighing of the potted plant was continued until the transpiration rate became constant. After attaining the constant value, the stem of plant was severed a few centimeters above its base and the fresh surface was quickly cut a second time under water again in order to exclude the air from its water-conducting system. The shoot was mounted in a potometer, was put carefully in place and reading was continued. In order to take into account the rate of water loss from the pot in the value of transpiration rate, the pot was weighed a number of times after applying vaseline to the cut surface of the stem. The rate of water loss from the pot was almost negligible when compared with the transpiration rate. Experimental results thus obtained with respect to one of each of the three species were shown in Figures 2 to 4. In every figure the exclamation mark (!) shows the instant of severance of the stem.

The transpiration rate after cutting is sometimes much higher or much lower than the value before cutting, and in some cases is almost equal to the value before cutting. After one or two hours the transpiration rate approaches the value before cutting within ±2.4 pct, except in case of *Cinnamomum camphora*, where wilting was observed only one hour after the cut as shown by the arrow in Figure 3. From these examinations, it is considered that a shoot mounted in a potometer will serve satisfactorily in our investigation, one or two hours after the cut, and wilting has not occurred.

Observation of stomata—The author observed the behavior of stomata of *Ilex rotunda Thunbergii*, using Suzuki's Universal Micro Printing (SUMP) method [*Kawakura*, 1931]. There are several methods for observing stomatal openings, such as *Stahl's* [1894] cobalt chloride method, *Darwin's* [1898] horn hygroscope method, *Lloyd's* [1908] alcohol method, *Darwin* and *Pertz's* [1911] porometer method [see also *Knight*, 1916], *Lloyd's* [1913] microscope method, infiltration methods [*Molisch*, 1912; *Monji*, 1938; *Stålfelt*, 1929b], and others. But the SUMP method was adopted because the permanent pattern of stomata can be taken in a short time by merely pressing a SUMP plate against the back of a leaf, and the pattern can be examined under a microscope. Care should be taken that a small portion of a leaf once patterned should not be used again to pattern the next SUMP plate, because the tissue of a leaf may be injured by the solvent of the first plate.

The enlarged microscopic photographs obtained by the experiment in full sunlight on Oct. 9, 1952

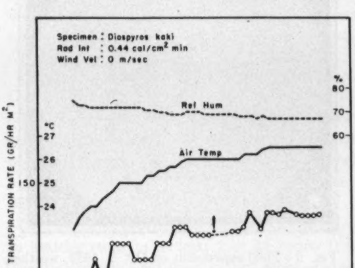

FIG. 4 – Transpiration rate before and after the severance of stem; ! shows the instant of severance; Sep. 22, 1953

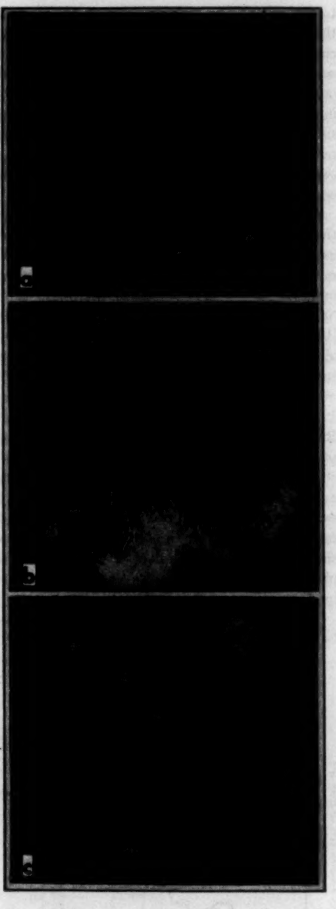

FIG. 5 – Field experiment on Oct. 9, 1952; weather, fair; stomata of a leaf (× 260) of *Ilex rotunda Thunbergii* (a) under natural conditions at 11h 10m (five minutes before severance of a branch); (b) at 12h 40m (85 minutes after severance); shoot without water-supply; (c) at 12h 40m (85 minutes after severance); shoot with water-supply

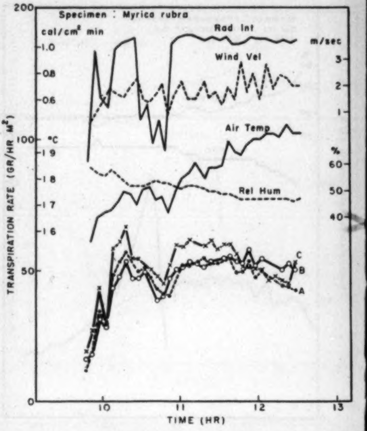

FIG. 6 – Transpiration rates of cut shoots treated by different ways; Oct. 12, 1952, fair, occasional clouds, field experiment; (A) cut under water; (B) cut under water after severance in air; (C) cut in air

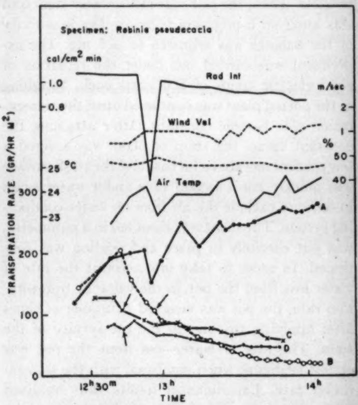

FIG. 7 – Transpiration rates of cut shoots treated by different ways; Oct. 28, 1952, fair, occasional clouds, field experiment; (A) cut under water; (B) cut under water after severance in air; (C) and (D) cut in air

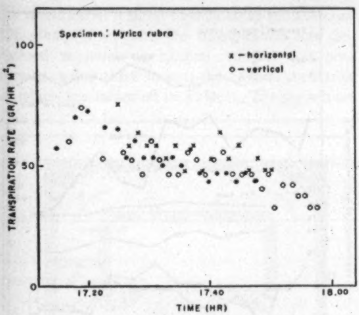

FIG. 8 – Transpiration rates of cut shoots under different water pressure; Aug. 6, 1951, fleecy clouds, field experiment

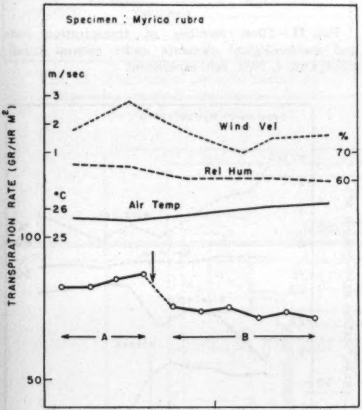

FIG. 9 – Effect of projection area against solar radiation upon transpiration rate; Oct. 18, 1951, fair, field experiment; (A) projection area maximum; (B) projection area minimum

in the open are shown in Figure 5. Air temperature, relative humidity, radiation intensity, and wind velocity during the observation were, 25.0–23.7°C, 54–57 pct, 0.89 cal/cm²min, and 0.3–1.0 m/sec, respectively.

We can see from these three photographs that the stomatal openings of the shoot without water supply were almost completely closed 85 minutes after the severance, but were wide open in case of the shoot with water supply. The commencement of wilting of leaves on the shoot without water was observed visually 35 minutes after the severance. The leaves of the shoot with water remained unwilted throughout our observation. From these observations, we can likewise say that a shoot mounted in a potometer can serve satisfactorily in our investigation if wilting does not occur.

TABLE 1 – *Various constants of shoots*

Shoot (1)	Diameter (2)	No. of leaves (3)	Total leaf area (4)	Projection area (5)	Ratio, col. 4 / col. 5	Transpiration rate	Remarks
	cm		cm²	cm²		gr/hr m²	
A	0.56	196	1421	305	0.22	53.6	same shoot
	0.56	196	1421	480	0.34	54.9	
C	0.55	46	548	215	0.39	39.3	
D	0.50	151	1048	445	0.42	38.9	

Cutting process of a branch—The cutting process of a branch must be examined in order to find out the most convenient and effective way to treat the shoot of various species under investigation. Five species, *Myrica rubra*, *Robinia pseudacacia*, *Podocarpus macrophyllus*, *Pinus Thunbergii*, and *Cryptomeria japonica*, were selected among; (1) the broad-leaved evergreens, (2) the broad-leaved deciduous trees, (3) the acerose trees. The march of transpiration rate of shoots treated in three ways, (1) cut under water, (2) cut under water after the cut in air, (3) cut in air, were compared under the same environmental conditions.

Figures 6 and 7 show the experimental results. Curves A, B, C, and D, show the march of transpiration rate of cut shoots treated in different processes: A, cut under water; B, cut under water one second after the cut in air; C and D, mounted in a potometer one and five seconds respectively after the cut in air.

In case of *Myrica rubra*, every shoot remained in healthy state for at least 2 or 2½ hours. It is easy to maintain a cut shoot for five hours or more in a healthy state.

In case of *Robinia pseudacacia*, only one cut shoot remained healthy at least for 1.5 hours, and three started to wilt at the instants shown by the arrows in Figure 7. Furthermore, it was found that the shoots of this species are very difficult to

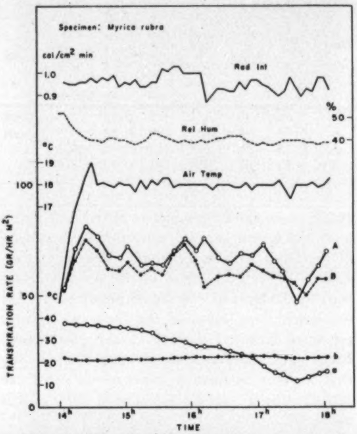

FIG. 10 – Transpiration rate of cut shoot under decreasing water temperature in potometer and that of under nearly constant water temperature; Feb. 4, 1952, laboratory experiment; curves a and b show the water temperature of A and B, respectively

maintain in healthy state more than an hour in full sunlight even when cut under water.

In case of *Podocarpus macrophyllus* and *Cryptomeria japonica*, three shoots out of four remained in a healthy state at least for two hours. In case of *Pinus Thunbergii*, two shoots out of four remained in a healthy state at least for three hours. Thus, the effect of cutting process on transpiration rate differs widely with different species. From this point of view, it is necessary to examine in advance the most appropriate cutting process with respect to the species to be investigated.

The effect of change of water pressure—This effect was studied using two types of potometer previously mentioned. Two shoots were mounted in the potometers separately, and the transpiration rate trends were compared in the open under the solar radiation through fleecy cloud with the air temperature of 29.5–29.0°C, the relative humidity of 66–73 pct, and the wind velocity of about three m/sec. Fairly good agreement was obtained, as shown in Figure 8.

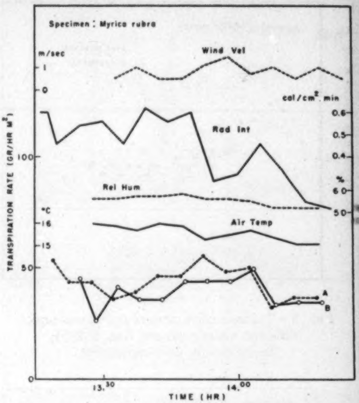

FIG. 11 – Time marches of transpiration rate and meteorological elements under natural conditions; Dec. 4, 1951, field experiment

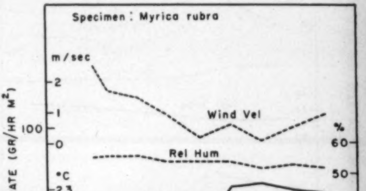

FIG. 12 – Lag period of transpiration rate affected by the variation of solar radiation; Oct. 31, 1951, field experiment

The effect of projection area receiving solar radiation—It is doubtful whether the leaf area or the projection area receiving solar radiation should be applied, in regard to radiation intensity, in calculating the transpiration rate from the amount of water absorbed by a shoot. The examination was carried out in the open with *Myrica rubra*. Figure 9 shows the results of one test. Part A shows the transpiration curve when the projection area is maximum, and part B when it is minimum. A small arrow head shows the instant of changing the direction of a shoot against solar radiation at 12h 49m. As a result, the transpiration rate decreased as much as 13 pct. Another test performed, using three shoots, the various constants of which are indicated in Table 1. The projection area of the first shoot was changed from 305 to 480 cm², equal to a 57.4 pct increase of the initial value, but there was no significant change in its transpiration rate. Furthermore, the transpiration rates of shoots C and D are in good agreement in spite of the ratio of projection area to total leaf area for shoot D exceeds shoot C by 7.7 pct. The transpiration rates of shoot A exceed that for shoots C and D by 40 pct in spite of fact that the ratios of projection area to total leaf area for shoot A are smaller than that for C and D, to an extent of 15 to 91 pct. The discrepancy is not accounted for. Thus, we can not say that the transpiration rate of shoot always increases or decreases in direct proportional relation to the ratio of projection area to total leaf area, but at least we have affirmed the fact that the effect of projection area sometimes attains an extent from 0 to 13 pct.

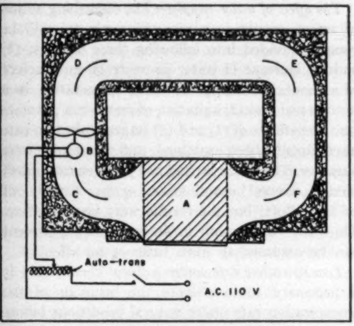
D
E
B
C
A
F
Auto-trans
A.C. 110 V

FIG. 13 – Plan view of the wind tunnel; A, measuring vessel; B, ventilator; C, D, E, and F, guide vanes

The effect of change of water temperature—Examination was carried out in the laboratory under the artificial radiation of eight electric lamps, totalling 4000 watts, with respect to two cut shoots of *Myrica rubra* under the same environmental conditions. The water temperature of one of these

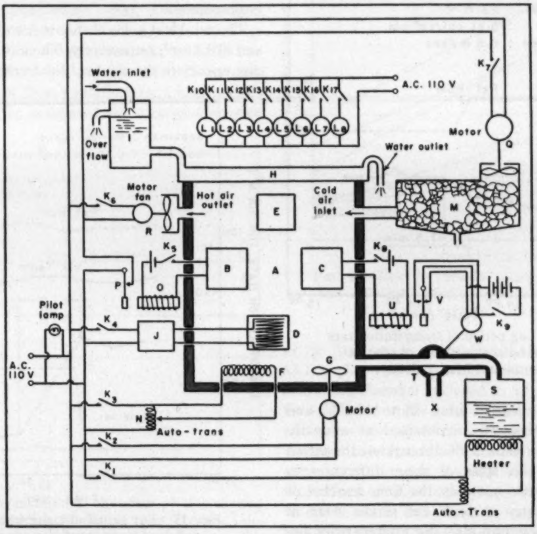
Water inlet
K10 K11 K12 K13 K14 K15 K16 K17
A.C. 110 V
K7
L1 L2 L3 L4 L5 L6 L7 L8
I
Over flow
Motor
Q
Water outlet
H
Motor fan
Hot air outlet
E
Cold air inlet
M
R
K6
K5
K8
B
A
C
P
O
U
V
Pilot lamp
K4
J
D
W
K9
A.C. 110 V
G
F
T
S
K3
N
Motor
X
Auto-trans
K2
Heater
K1
Auto-Trans

FIG. 14 – Electric circuit arrangements and piping of the experimental apparatus

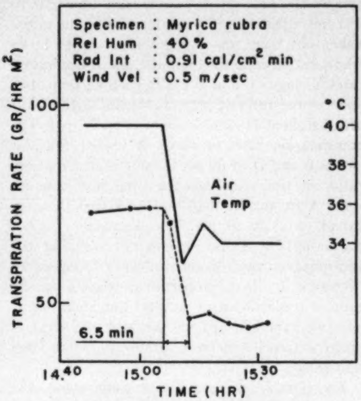

FIG. 15 – Lag period of transpiration rate affected by the variation of air temperature, Feb. 19, 1953

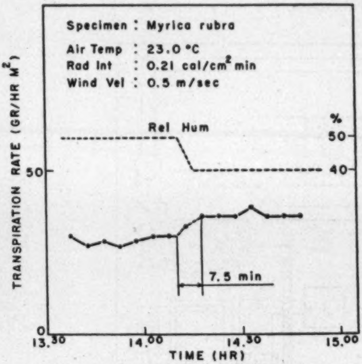

FIG. 16 – Lag period of transpiration rate affected by the variation of relative humidity, Mar. 2, 1953

potometers was varied from 38 to 11.2°C, and that of the other was maintained at a nearly constant value within ±1°C throughout the period of experiment. In spite of these differences in water temperature not only the time marches of transpiration rates in both cut shoots were in parallel tendency but also the discrepancies between two transpiration rates were indistinct. The results are shown in Figure 10. It is suggested that the temperature of water absorbed in the water-conducting system of the stem of cut shoot from its cut end is soon equalized with that of air by heat conduction between bark and air before arriving at the leaves.

The effect of water-supply—The disturbing action of water supply in a measuring pipette will be roughly divided into following three actions: (1) sudden increase of water pressure on cut surface of a shoot; (2) change of water temperature in a potometer; and (3) agitation of water in a potometer. The effects of (1) and (2) on transpiration rate have already been examined, and the results were negative. The effect (3) had not yet been examined. Hence, several examinations were carried out on this effect, but the results were also negative. Thus, the water supply in the course of experiment can be assumed to have little or no effect.

Transpiration rate under natural conditions—It is necessary to investigate the behavior of the transpiration rate under natural conditions before starting our laboratory experiments in order to obtain rough information in advance. Figure 11 is one example of the experimental results with respect to the cut shoots of *Myrica rubra* mounted in potometers.

The total leaf areas of shoots A and B are 1120.6 and 870.5 cm², respectively. There is no significant discrepancy in the values of the transpiration rates.

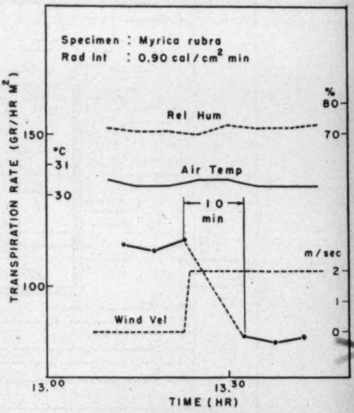

FIG. 17 – Lag period of transpiration rate affected by the variation of wind velocity, July 31, 1953

In addition both transpiration curves follow approximately parallel courses. It can also be seen that the variation of transpiration rate is correlated mainly to the variation of the intensity of solar radiation and the air temperature, the former variation following about ten minutes behind the latter variation.

Figure 12 shows the experimental result of the effect of the solar radiation on transpiration rate. The solar radiation was suddenly screened by a sheet of drawing paper hung about one meter in front of the potometer at the instant shown by a small arrow head (12h 33m). The transpiration rate fell to a value equal to 35.5 gr/hrm² from 53.2 gr/hrm² about ten minutes after the screening. Thus, the transpiration rate of ***Myrica rubra*** varies with the intensity of solar radiation. The time lag was about ten minutes.

As the transpiration rates under natural conditions are affected simultanuously by the complicated change in the environmental conditions as shown above, it is difficult to separate these effects of environmental conditions from such a simple experiment. For that reason, the author has investigated the relation between transpiration rate and various meteorological elements one by one using a hand-made small Göttingen-type wind tunnel in which one can change the radiation intensity, the air temperature, the relative humidity, and the wind velocity at will, or can maintain any of these conditions for a long period.

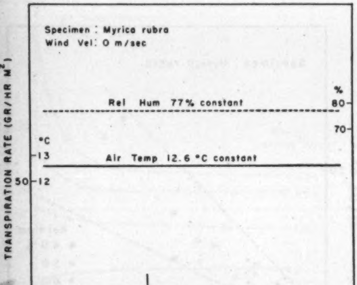

Fig. 18 – Examination of the effect of illuminating lamp necessary to light in dark to take readings, Dec. 4, 1951; small arrow shows instant of lighting 100-watt electric lamp

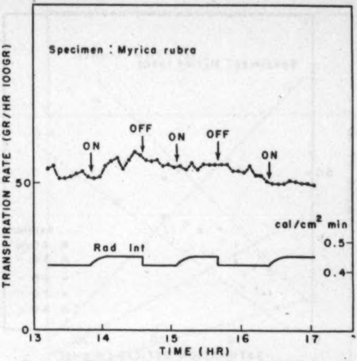

Fig. 19 – Examination of the effect of wave-length of light, June 2, 1954, ON and OFF relate to the 250-watt high-pressure mercury vapor lamp

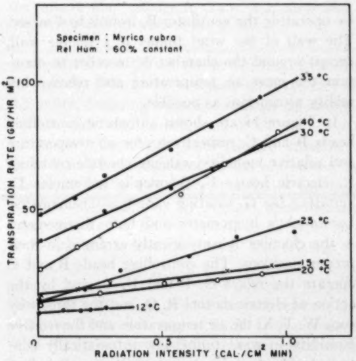

Fig. 20 – Relation between transpiration rate and radiation intensity, Mar. 10 to Apr. 10, 1953; wind velocity, 0.5 m/sec

Apparatus for measuring the transpiration rate as the function of meteorological elements—Figure 13 is a plan view of a wind tunnel. Part A is the measuring chamber enclosed in glass plates at its fore side and upper side. A shoot mounted in a potometer was placed in this chamber after being mounted in a stand, and the potometer readings were taken through the fore side window. The dimensions of this chamber are 63 cm in height, 46 cm in width, and 46 cm in length. The circuit length of wind tunnel is 4.7 m, and the wind velocity at the center of chamber A can be varied,

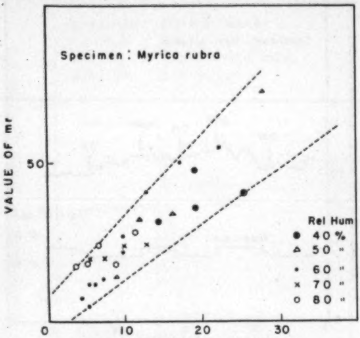

FIG. 21 – Relation between saturation deficit of atmosphere and value of m_r; wind velocity, 0.5 m/sec

by operating the ventilator B, from 0 to 4 m/sec. The wall of the wind tunnel is a double wall, except around the chamber A, in order to maintain the inner air temperature and relative humidity as constant as possible.

In Figure 14 are shown automatic controlling heads B and C, respectively, for air temperature and relative humidity, calcium chloride container E, electric heater F, thermopile radiometer D, agitating fan G, rotating vane-type anemometer, Lambrecht's hygrometer and bulb thermometer in the chamber A conveniently arranged in their proper positions. The controlling heads B and C operate the relays O, P and U, V, and by the action of electric motors R, Q, and the three way cock W, T, X, the air temperature and the relative humidity in wind tunnel are automatically controlled. M is an ice box and S a small boiler; L_1 to L_8 are electric lamps, 500 watts each, and H the water filter. I is a constant-level tank in order to supply water in the water filter H; J is an automatic recorder of the thermopile radiometer D; K_1 to K_{17} show the electric switches. The water supply in a potometer can be maintained by a small rubber tube inserted from the exterior into the chamber A. The small agitating fan G was not operated after the commencement of our experiment for it disturbs the air flow in the wind tunnel.

The lag period of the transpiration rate caused by the sudden change of meteorological elements was investigated by this wind tunnel.

Figures 15 to 17 show the results obtained on *Myrica rubra* by changing the air temperature, the relative humidity, and the wind velocity one by one in the wind tunnel. It takes a few minutes to change these elements in the wind tunnel. In spite of this disadvantage, these lag periods were 6.5, 7.5, and 10 minutes, respectively, as shown. Thus, the lag periods of transpiration rate in case of changing the meterological elements can be considered as 6.5 to 10 minutes.

Relations between transpiration rate and air temperature and relative humidity—With regard to the relation between transpiration rate and air temperature, 15 experiments were carried out on *Myrica rubra* during the period from Feb. 11 to Mar. 9, 1953, under the constant wind velocity of 0.5 m/sec, changing air temperature under constant radiation intensity and relative humidity. With regard to the relation between transpiration rate and relative humidity, 22 experiments were carried out on the same species during the period from Feb. 24 to Apr. 8, 1953 under constant wind velocity of 0.5 m/sec, changing relative humidity under constant radiation intensity and air temperature. The trends appear rather complicated in the relation between transpiration rate and air temperature. It is possible to obtain the experimental formulas necessary to estimate the transpiration rate but the error may be large because of the non-linearity of the trends. Consequently, the author has searched for the other functional relations to obtain more accurate formulas to estimate the transpiration rate.

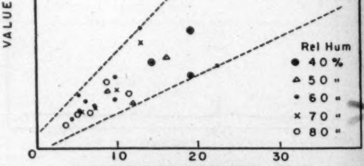

FIG. 22 – Relation between saturation deficit of atmosphere and value of n_r; wind velocity, 0.5 m/sec

Relation between transpiration rate and radiation intensity—Before starting our laboratory experiments on this relation, it is necessary to examine the effect of illumination in order to take readings in the dark and the effect of wave lengths of light on the transpiration rate.

Figure 18 shows the result of an experiment to examine the effect of illumination necessary to take readings in the dark. A shoot of *Myric rubra* was mounted in a potometer and carried into a dark room. After the transpiration rate had attained its steady value, a 100-watt electric lamp about a meter above the shoot was switched on at the instant shown by a small arrow. The light had little effect. A 40-watt lamp was employed to take readings in the dark.

To examine the effect of wave length of light upon transpiration rate, a 250-watt high-pressure mercury lamp was employed in addition to eight incandescent electric lamps which were switched on throughout the experiment. Switching the mercury lamp on and off, four experiments were performed using *Myrica rubra*. Figure 19 shows the results of one test obtained under the conditions of 30°C, 80 pct humidity, and 1 m/sec air velocity. A small effect of the mercury lamp seems to exist, but it is not significant as Iwanov and Thielmann had reported.

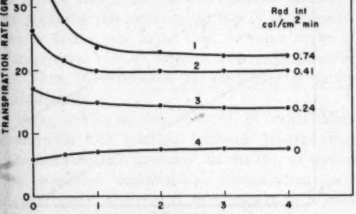

FIG. 23 – Relation between transpiration rate and wind velocity; Jan. 19 to Mar. 17, 1954

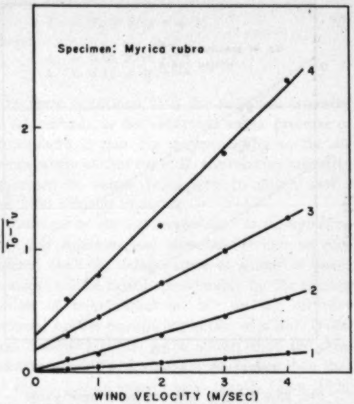

FIG. 24 – Relation between wind velocity and the ratio of wind velocity to ($T_0 - T_v$); curve number corresponds to that of in Fig. 23

With regard to the relation between transpiration rate and radiation intensity, 27 experiments were carried out during the period from Mar. 10 to Apr. 10, 1953 under constant wind velocity of 0.5 m/sec, changing radiation intensity by switching the eight electric lamps on or off under constant air temperature and relative humidity. Only 7 of 27 experimental results are shown in Figure 20. As in this figure, the trends are best represented graphically by straight lines without exception. Let T be the transpiration rate, and R be radiation intensity, then the relation is

$$T = m_r R + n_r \tag{1}$$

where m_r is the slope and n_r the intercept on the ordinate. The values m_r and n_r are both increased with higher air temperature and decreased with higher relative humidity, as it can be seen in the figure, that is, the values m_r and n_r are the functions of air temperature and relative humidity.

Consequently, the method of least squares was employed to obtain the values of m_r and n_r from 27 experiments. The factor having a high degree of correlation was sought. The saturation deficit of atmosphere was found to be a factor having a high degree of linear correlation with the values of m_r and n_r, as shown in Figures 21 and 22. Obviously there is a direct relation between m_r or n_r and saturation deficit, notwithstanding the scatter. The different symbols show that the scatter has no direct connection with relative humidity.

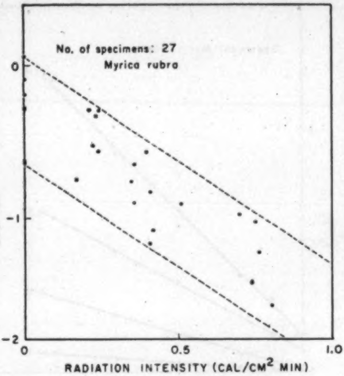

FIG. 25 – Relation between logarithmic value of gradient a and radiation intensity

Again considering the trends as straight lines and employing the method of least squares, the empirical formulas for m_r and n_r were obtained as the function of the saturation deficit H_d of atmosphere. Note that the relation of n_r to H_d was obtained in type of $n_r = s \cdot H_d$, where s indicates the gradient, for the value n_r is the value of transpiration rate under zero radiation intensity and should be considered as zero when H_d is zero.

For *Myrica rubra* (wind velocity = 0.5 m/sec)

$$\left.\begin{aligned} m_r &= 2.13\, H_d + 2.65 \\ n_r &= 1.99\, H_d \end{aligned}\right\} \qquad (2)$$

mean error of m_r = 5.51; mean error of n_r = 5.13.

By substituting these in (1), we obtain an equation representing the transpiration rate T as the function of radiation intensity R (cal/cm^2-min) and saturation deficit H_d (mmHg) for *Myrica rubra* (wind velocity = 0.5 m/sec), as

$$T = (2.13\, R + 1.99)\, H_d + 2.65\, R \qquad (3)$$

mean error of T = 5.60

The saturation deficit of atmosphere H_d can be represented as the function of saturated vapor pressure e_s (mmHg) and relative humidity $H_r \times 100$, as

$$H_d = e_s\,(1 - H_r) \qquad (4)$$

By (3) and (4), we can easily estimate the transpiration rate of *Myrica rubra* under wind velocity of 0.5 m/sec for any radiation intensity, air temperature, and relative humidity.

Relation between transpiration rate and wind velocity—In regard to this relation, 27 experiments were carried out during the period from Jan. 19 to Mar. 17, 1954 with respect to ***Myrica rubra***. Only four experimental results are shown in Figure 23.

The transpiration rate decreases rapidly with higher wind velocity within the range of 0–1 m/sec and approaches a constant value asymptotically within the range of 1–4 m/sec. Furthermore the rate of decrease in transpiration rate diminishes with lower intensity of radiation except in case of 0 cal/cm^{2}min. In this case, 0 cal/cm^{2}min, the transpiration rate increases with higher wind velocity.

In order to obtain the empirical formula for these curves, let us put v as the wind velocity and represent the transpiration rate at $v = 0$ with T_0 and at $v = v$ with T_v, and calculate the value of $v/(T_0 - T_v)$. The rleation between this value and wind velocity can be best represented by a straight line, as shown in Figure 24. Hence, the trends can be represented by

$$v/(T_0 - T_v) = a \cdot v + b \qquad (5)$$

where a is the gradient of the straight line and b the intercept on the ordinate. The values of a and b decrease with higher intensity of radiation. The method of least squares was employed to obtain the values of a and b with respect to the 27 experiments. It was found that the logarithmic values

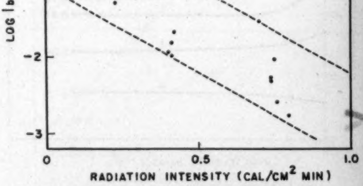

FIG. 26 – Relation between logarithmic value of Y-intercept b and radiation intensity

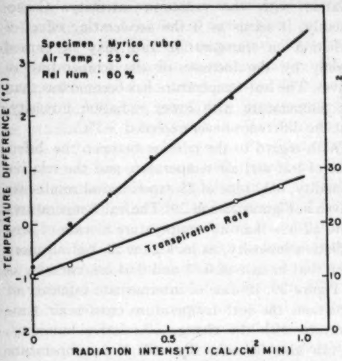

FIG. 27 – Relations between the difference of leaf and air temperature or transpiration rate and radiation intensity; Mar. 28, 1953, laboratory experiment; air temperature, 25°C; relative humidity, 80 pct; wind velocity, 0.5 m/sec

of a and b were in linear relation with the radiation intensity, as shown in Figures 25 and 26. The gradient and the value of intercept on the ordinate were calculated by the method of least squares, and the empirical formula of the transpiration rate T (gr/hrm²) were obtained from (5) as the function of wind velocity v (m/sec) and radiation intensity R (cal/cm² min) for *Myrica rubra*, as follows

$$T_v = T_0 \mp v/(0.55 \times 10^{-1.37R} \cdot v + 0.32 \times 10^{-2.35R}) \qquad (6)$$

where T_0 (gr/hrm²) is the transpiration rate under zero wind velocity and it is the function of air temperature, relative humidity, and radiation intensity. The positive sign after T_0 in (6) should be applied only in case of zero radiation intensity. By applying this equation to the 27 experiments one by one, it was found that the mean errors of transpiration rate lie between 0.02 and 0.35 gr/hr m². Thus, (6) represents the experimental results satisfactorily.

Now, modifying the data of 27 experiments concerning the relation between transpiration rate and radiation intensity, by the (6), we obtain the equation representing transpiration rate T_0 (gr/hrm²). The results with respect to *Myrica rubra* are as follows

$$T_0 = (2.09\,R + 1.67)\,H_d + 35.62\,R \qquad (7)$$

where

$$H_d = e_s\,(1 - H_r)$$

and

$$T = T_0 \mp v/(a \cdot v + b) \qquad (8)$$

where

$$a = 0.55 \times 10^{-1.37R}$$
$$b = 0.32 \times 10^{-2.35R}$$

In these equations, R is the radiation intensity in cal/cm²min, e_s the saturated vapor pressure of atmosphere in mm Hg corresponding to the air temperature at that time, H_r the relative humidity expressed in values from zero to unity, and v the wind velocity in m/sec.

Relations of the leaf temperature to transpiration rate and meteorological elements—It can be considered that the temperature of a leaf in direct sunlight will be raised considerably by the heating action of solar radiation, but on the contrary reduced by the transpiring action of a leaf. *Miller* and *Saunders* [1923] have shown that the temperature of wilted leaf is always higher than that of turgid leaf in case of crop plants. *Clum* [1926] has shown that the temperature of leaves of *Fuchsia speciosa*, *Phaseolus vulgaris*, *Brassica oleracea*, and *Syringa vulgaris* were nearly always warmer than the air during the day, and in direct sunlight they were frequently warmer than the air by 5 to 10°C. *Copeland* [1932] has measured the temperature of the leaves of chaparral shrubs by wrapping a leaf around the bulb of a ordinary thermometer and had reported that the temperature of the leaves in direct sunlight was sometimes higher by as much as 10°C than the shade temperature. *Martin* [1935] has also measured the leaf

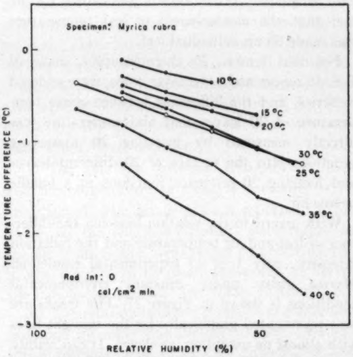

FIG. 28 – Relations between the difference of leaf and air temperature and air temperature and relative humidity; Mar. 26 to Apr. 8, 1953, laboratory experiment; wind velocity, 0.5 m/sec.

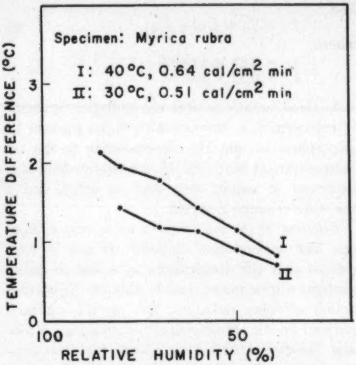

FIG. 29 – Relation between the difference of leaf and air temperature and relative humidity; Mar. 26 to Apr. 8, 1953, laboratory experiment; wind velocity, 0.5 m/sec

temperature of *Helianthus annuus* using thermocouple and reported "the temperature of leaves hanging nearly at right angles to the Sun's rays in the open averaged about 1°C above that of the air, while that of leaves under tent was about 5°C below." Thus, the leaf temperature varies widely with the amount of transpiration and the change of environmental conditions. The regular relations of the leaf temperature to transpiration rate or to meteorological elements had not yet been found. The irregularity of the results was caused by the fact that the measurement of leaf temperature was made on an individual leaf.

For that reason, 20 thermocouples, made of B.S. 36 copper and constantan wires, were soldered in series, and the difference between mean temperature of 20 leaves and air temperature was directly measured by inserting 20 measuring junctions into the surface of 20 different leaves and hanging 20 reference junctions in a bundle in free air.

With regard to the relation between the difference of leaf and air temperature and the radiation intensity, only 1 of 13 experimental results on *Myrica rubra* under constant environmental conditions is shown in Figure 27. The trends are best represented graphically by the straight lines with almost no exception, as shown. It can readily be understood that the difference of leaf and air temperature is in direct proportion to the transpiration rate. The transpiration rate is also in linear relation with the radiation intensity. Consequently, it seems as if the accelerating effect of radiation on transpiration rate may be caused mainly by the increase of the temperature of leaves. The leaf temperature has become less than air temperature with lower radiation intensity, but the difference never exceeded −3°C.

With regard to the relation between the difference of leaf and air temperature and the relative humidity, only nine of 25 experimental results are shown in Figures 28 and 29. The leaf temperatures were all less than air temperature in case of zero radiation intensity, as in Figure 28, but all more than that in case of 0.51 and 0.64 cal/cm^{2}min, as in Figure 29. In case of intermediate intensity of radiation, the leaf temperature crosses air temperature with the change of relative humidity. It can also be seen that the leaf temperature acceleratively decreases with higher air temperature and increases almost in linear trends with the increase of relative humidity. This tendency is quite opposite to that of the transpiration rate.

From these results, it can be suggested that the leaf temperature would be decreased linearly with the increase of the saturation deficit of atmosphere and with the decrease of radiation intensity. This was confirmed by dividing the radiation intensity in steps of 0.1 cal/cm^{2}min and rearranging the experimental data in these steps, but only a part of the results were shown in Figure 30.

The values of radiation intensity indicated in

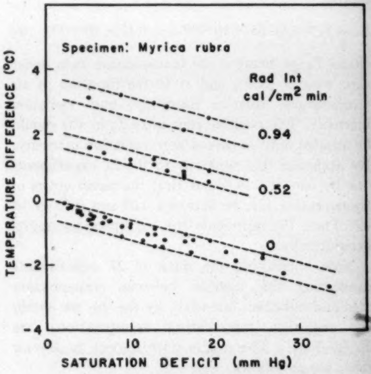

FIG. 30 – Relation between the difference of leaf and air temperature and saturation deficit of atmosphere; wind velocity, 0.5 m/sec

the figure are the mean value of radiation intensity corresponding to each plotted point. Now, we can see that not only the leaf temperature decreases in nearly direct proportion to the saturation deficit but also the whole trend rises with higher radiation intensity, as has already been expected. The gradients of trends seem to have no connection with radiation intensity. Provided that the gradients are constant with regard to the radiation intensity, the inclinations of the straight lines representing the relation between the difference of leaf to air temperature and the radiation intensity will have no relation with air temperature and relative humidity under constant wind velocity.

With regard to the relation between the difference of leaf and air temperature and the wind velocity, only four of 25 experimental results are shown in Figure 31. These trends closely resemble that of the relation between transpiration rate and wind velocity. The leaf temperature decreases rapidly with higher wind velocity within the range of 0–1 m/sec and very slowly beyond this wind velocity when the radiation intensity is not zero, but on the contrary increases when the radiation intensity is zero. This effect is violent with higher radiation intensity. It seems probable that the wind causes the circulation of air around the leaves to conduct heat from air to the leaf surface when the temperature of the leaf is lower than that of surrounding air but to conduct heat from leaf surface to air when the temperature of leaves is higher than that of surrounding air, until the equilibrium is attained between the leaf temperature and the air temperature. It also seems probable that the transpiration rate lags behind the change of the leaf temperature.

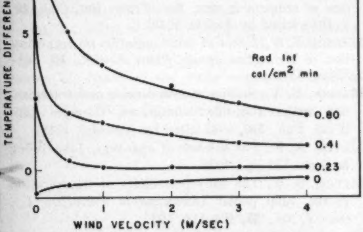

FIG. 31 – Relation between the difference of leaf and air temperature and wind velocity; Jan. 21 to Mar. 17, 1954; laboratory experiment

As we have described above, there are close correlations between mean temperature of leaves, transpiration rate, and meteorological elements. The relation between them follows a regular trend. It should be noted that the mean temperature of leaves had been determined by only 20 thermocouples inserted into 20 different leaves, and the total number of leaves amounts to 80–250 in case of shoot of *Myrica rubra*. Accordingly, it is still doubtful whether the measured values will give the true mean temperature of whole leaves of a shoot or not.

Summary of the experimental results—In this report, the relations between transpiration rate and meteorological elements were studied in order to derive the experimental formulas useful to estimate the total amount of transpiration from a forest under optional meteorological conditions. The following results were obtained.

(a) The transpiration rate of a shoot mounted in a potometer agrees within ±2.4 pct of that of a potted plant and the stomatal openings are in a healthy state provided one or two hours has elapsed after the cut of a branch, and wilting has not occurred.

(b) The effects of cutting process, water pressure, projection area against solar radiation, water temperature, water supply, were examined in order to confirm the reliability of potometer method. The cutting process was different for various species and at least 0–13 pct change in transpiration rate in case of changing projection area against solar radiation was found, but the effect of water pressure, water temperature, and water supply were negative.

(c) The relations between transpiration rate and air temperature or relative humidity were investigated. The details are not reported in this paper, for the relations especially with regard to the air temperature, were rather complicated and it was thought to be disadvantageous to derive the empirical formula by these relations.

(d) The relation between transpiration rate and radiation intensity was further studied. The empirical formula, $T = (2.13\ R + 1.99)\ H_d + 2.65\ R$, was obtained for *Myrica rubra*, under the constant wind velocity of 0.5 m/sec, where R is the radiation intensity, and H_d the saturation deficit of atmosphere.

(e) The relation between transpiration rate and wind velocity was studied. The empirical formulas necessary to estimate the transpiration rate T under optional meteorological conditions were

$$T = T_0 \mp v/(0.55 \times 10^{-1.37R\cdot v} + 0.32 \times 10^{-2.35R}) \quad (6)$$

$$T_0 = (2.09\ R + 1.67)\ H_d + 35.62\ R \quad (7)$$

(f) Finally, the relations of the leaf temperature to transpiration rate and meteorological elements were studied, using 20 pairs of copper-constantan thermocouples in series, and showed that the linear relationship holds between leaf temperature and transpiration rate and the systematic relations hold between leaf temperature and meteorological elements closely resembling the relation between transpiration rate and meteorological elements.

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The Total Transpiration from a Forest

YOSHITO YAMAOKA

Abstract—The investigation on the relation between total leaf weight and breast-height diameter is necessary to estimate the total transpiration. The method of estimating the total leaf weight of *Cryptomeria japonica* was discussed, and this was found to be proportional to the square of the breast-height diameter. The relations between transpiration rate and the meteorological elements regarding to this species were also investigated, and the empirical formulas necessary to estimate the total transpiration were obtained. Finally, a stand of 740 *Cryptomeria japonica* (4376 sq m; about 1.1 ac) 45 years old was selected, for example, and the total leaf weight was estimated at 69 tons and the total transpiration at 1.80 ton/hour in case of air temperature, 26.6°C; relative humidity, 80 pct; wind velocity, 3.5 m/sec; and radiation intensity, 1 cal/cm^2 min. This value was compared with the water loss from various types of surfaces to show no serious error exists in our estimation.

The relations between leaf temperature and transpiration rate and meteorological elements were also investigated.

Introduction—In the previous report [*Yamaoka*, 1957] the experimental formulas necessary to estimate the total transpiration from a forest of *Myrica rubra* were obtained. Unfortunately, no reforestation of this specis can be found in our area. This species was selected only for the reason that it is grown in the yard near our laboratory and is one of the easiest species in treatment of their shoots. Using this species, the fundamental research for estimating the total transpiration from a forest has been accomplished. Accordingly, the author intends to estimate the total transpiration from a stand or forest of *Cryptomeria japonica* in Namera National Forest, Compartment 27, Yamaguchi District, Japan, where the author once surveyed the distribution of breast-height diameters.

In order to carry out the work, it is necessary to obtain the relation between total leaf area and breast-height diameter of this species. There have been several investigations in regard to the measurement of total leaf area of broad-leaved trees and conifers performed by, *Baker* [1948], *Buchanan* [1936], *Burger* [1938], *Dengler* [1937], *Kadota* [1950], *Kittredge* [1944], *Kozlowski* [1943], *Yamaoka* [1952], and others, but there has been no investigation useful to our work in regard to *Cryptomeria japonica*. Consequently, the author has measured the total leaf amount of this species. Since it was difficult to measure the total leaf area because its countless short needles lie upon one another and have no distinct boundary around each needle, the author was compelled to measure the total leaf weight instead of the total leaf area. It has already determined from several other species that a linear relation holds between leaf area and its weight, so it can be expected that the same relation will hold in case of this species.

Boundary of leaves—There is no distinct boundary between leaves and green bark on the stem of a twig of the *Cryptomeria japonica* unlike the broad-leaved trees and pine trees. The green bark is stripped off in irregular shape when the needles are torn from the stem of the twig. In addition, it is not only almost impossible to count the number of needles, but also to tear off these innumerable needles.

Examining the branch in detail, it is found that the color of bark with needles is green and without needles is brown. The boundary between these barks is distinct. As most of the green bark is stripped off with the needles, the author decided to measure the total leaf weight together with the green bark. It is almost impossible to strip off all of the green bark together with the needles, therefore the author has searched for some convenient relation between total leaf amount and another factor which makes it possible to measure the total leaf weight. It was found that the total weight of a branch cut off at the boundary of green and brown bark is directly related to its woody tissue (Fig. 1).

The total weight of the woody tissue is approximately ten per cent of the total weight of a branch having green bark. Accordingly, it became possible to determine the total leaf weight by subtracting ten per cent of the whole weight of a branch having green bark.

Relations of the total leaf weight to age and sectional area of stem just under the crown—It has already

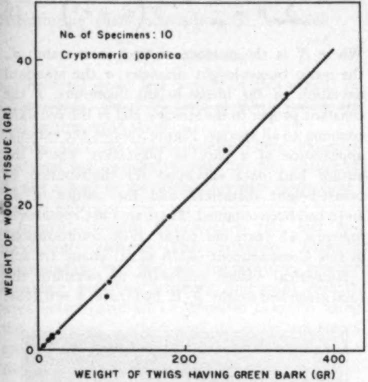

FIG. 1 – Relation between fresh weight of twig having green bark and fresh weight of their woody tissue; surveyed in Nov. 1952

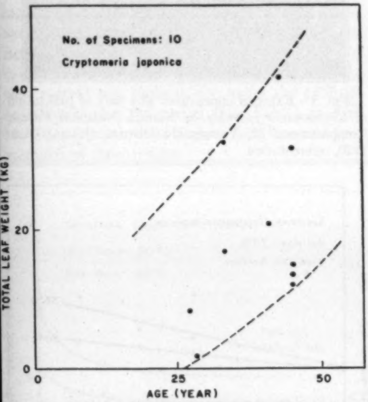

FIG. 2 – Relation between total leaf weight and age; surveyed Nov. 26 to Dec. 4, 1952

been described [*Yamaoka*, 1952] that the total leaf area of some broad-leaved trees and pine trees were in direct proportion to the sectional area of stem just under the crown, but that there was no significant correlation between the total leaf area and age. Accordingly, similar relations for *Cryptomeria japonica* were investigated.

A large part of *Cryptomeria japonica* actually surveyed were the trees growing closely in a row and had been cut at the tips of the stem several times, but not in the past five or six years. The results obtained from ten of these *Cryptomeria japonica* with ages from 27 to 45 years, are shown in Figures 2 and 3. Figure 2 shows the relation between total leaf weight and age. Figure 3 shows the relation between total leaf weight and sectional area of stem just under the crown.

The values of total green leaf weight used in Figures 2 and 3 were obtained by subtracting ten per cent from the total weight of branches having green bark. Cones and flowers were removed before weighing. The trend is linear in Figure 3, but no significant correlation can be seen in Figure 2, which is consistent with the relations for broad-leaved trees and pine trees. Let us consider the trend in Figure 3 as a straight line passing through the origin and calculate its gradient k by means of the method of least squares. The relation between total green leaf weight W (Kg) and diameter of stem just under the crown d_0 (cm) can be expressed by

$$W = k \cdot \frac{\pi}{4} \cdot d_0^2 = 0.2134 \times \frac{\pi}{4} \cdot d_0^2 \qquad (1)$$

mean error of $W = 1.306$ Kg

It has already been reported [*Yamaoka*, 1952] that the breast-height diameter d (cm) can be expressed by $d = m \cdot d_0$, where m is the constant

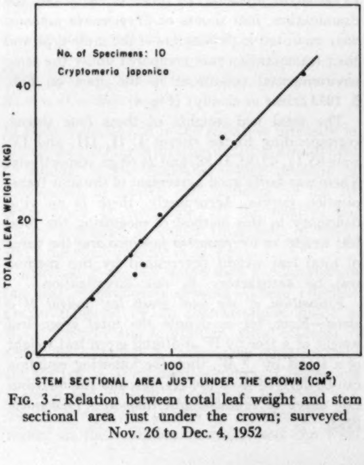

FIG. 3 – Relation between total leaf weight and stem sectional area just under the crown; surveyed Nov. 26 to Dec. 4, 1952

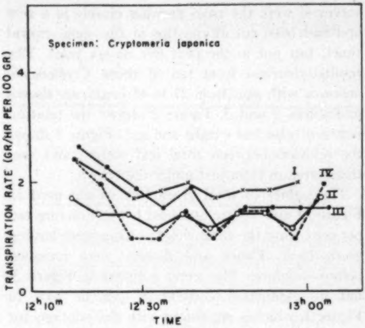

FIG. 4 - Amount of transpiration per 100 gr of green leaf weight per hour

common to all species. The value of m was calculated from 31 experimental data by means of the method of least squares and was found to be 1.110.

Accordingly, we have

$$d = m \cdot d_0 = 1.110\, d_0 \qquad (2)$$
$$\text{mean error of } d = 0.80 \text{ cm}$$

Examination of the method for measuring the total leaf weight—It is necessary to examine whether the total leaf weight determined by means of the convenient method described above will serve satisfactorily to measure the transpiration rate of *Cryptomeria japonica*. In order to carry out the examination, four shoots of *Cryptomeria japonica* were mounted in potometers of the same type and their transpiration rate compared under the same environmental conditions in the open on Feb. 5, 1953 (clear or cloudy) (Fig. 4).

The total leaf weights of these four shoots, corresponding to the curves I, II, III, and IV, were 85.11, 42.30, 31.88, and 24.68 gr, respectively. There was fairly good agreement of the four transpiration curves. Accordingly, there is no vital deficiency in this method of measuring the total leaf weight of *Cryptomeria japonica* and the value of total leaf weight determined by this method will be satisfactory in our investigation.

Estimation of the total green leaf weight of a stand—Now, let us denote the total green leaf weight of a tree by W and total green leaf weight of a stand by $\sum W$, then the following equation can be derived from the (1), (2), and the distribution curve of breast-height diameters [*Yamaoka*, 1952].

$$\sum W = \frac{k}{m^2} \cdot \frac{\pi}{4} \cdot N\left(d_m^2 + \sigma^2\right) \qquad (3)$$

Where N is the number of trees in a stand, d_m the mean breast-height diameter, σ the standard deviation of the breast-height diameters, k the constant proper to the species, and m the constant common to all species. Figure 5 shows the external appearance of a part of plantation where the author had once surveyed the distribution of breast-height diameters and the values of d_m and σ had been obtained. There are 740 *Cryptomeria japonica* 45 years old (Mar. 1910, reforestation) in this Compartment (4376 sq m; about 1.1 ac).

Numerical values necessary to calculate the total green leaf weight $\sum W$ by (3) are: $k = 0.2134$,

FIG. 5 - External appearance of a part of plantation of *Cryptomeria japonica* in Namera National Forest, Compartment 27, Yamaguchi District, Japan; Mar. 1910, reforestation

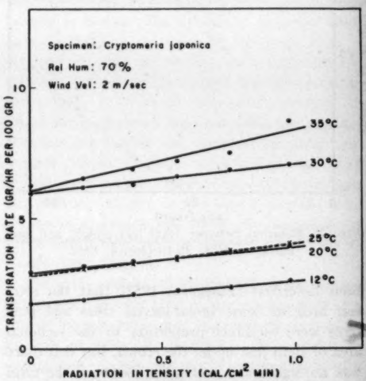

FIG. 6 - Relation between transpiration rate and radiation intensity; Feb. 24 to Apr. 16, 1954, laboratory experiment

$m = 1.110$, $N = 740$, $d_m = 24.45$ cm, $\sigma^2 = 86.80$. Substituting these values into (3), we have

$$\sum lW = 68914 \text{ Kg} \tag{4}$$

as the total green leaf weight of this stand. In other words, about 69 tons of green leaves are held on this small stand.

Note that the value obtained here indicates the total leaf weight in 1951 for the values of d_m and σ used in the calculation were those measured in 1951.

Relations between transpiration rate and meteorological elements—The relations between transpiration rate and air temperature, relative humidity, radiation intensity, and wind velocity were investigated on *Cryptomeria japonica* using the potometer method and the same apparatus used for *Myrica rubra* [*Yamaoka*, 1957]. As the trends closely resembled the trends in case of *Myrica rubra*, the author derived the empirical formulas from the relations between transpiration rate and radiation intensity and wind velocity.

The effects of illuminating lamps to take readings in the dark and the wave lengths of light were first examined and found little or no effect. Accordingly, 19 and 26 experiments with regard to the radiation intensity and the wind velocity were carried out, respectively, under the artificial radiation during the period from Feb. 1 to Apr. 16, 1954. Figures 6 and 7 show only five and four examples of these results.

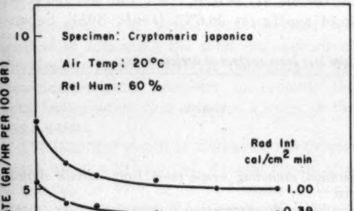

FIG. 7 – Relation between transpiration rate and wind velocity; Feb. 1 to Mar. 31, 1954, laboratory experiment

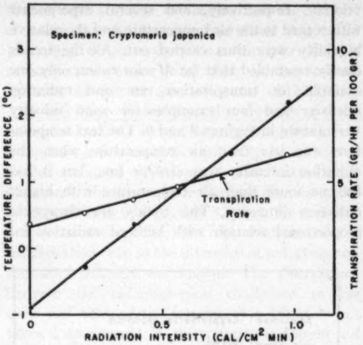

FIG. 8 – Relations between the difference of leaf and air temperature or transpiration rate and radiation intensity; Apr. 14, 1954, laboratory experiment; air temperature, 35°C; relative humidity, 40 pct; wind velocity, 2 m/sec

Considering now, the trends in Figure 6 as straight lines and the wind velocity v in proportional relation with the value $v/(T_0 - T_v)$, where T_0 represents the transpiration rate at zero wind velocity and T_v at any wind velocity v, the following empirical formulas can derived as in the case of *Myrica rubra* [*Yamaoka*, 1957].

$$T_v = \mathrm{T}_0 \mp v/(2.77 \times 10^{-0.96\, R} \cdot v + 2.16 \times 10^{-1.45\, R})$$

where

$$T_0 = (0.14\, R + 0.35)\, H_d + 3.08\, R \tag{5}$$

and

$$H_d = e_s\,(1 - H_r)$$

In these equations, R is the radiation intensity in cal/cm²min, H_d the saturation deficit of atmosphere in mmHg, e_s the saturated vapor pressure of atmosphere in mmHg corresponding to the air temperature at that time, H_r the relative humidity expressed in values from zero to unity, and v the wind velocity in m/sec.

Relations of the leaf temperature to transpiration rate and meteorological elements—These relations are investigated by 20 thermocouples made of B.S. 36 copper and constantan wires, soldered in series, by inserting 20 measuring junctions into the surface of 20 different needles of *Cryptomeria japonica* and hanging 20 reference junctions in a bundle in free air. 16 and 21 experiments with regard to the radiation intensity and the wind velocity, respectively, and several experiments with regard to the air temperature and the relative humidity were thus carried out. As the trends closely resembled that for *Myrica rubra*, only one example for transpiration rate and radiation intensity and four examples for wind velocity were shown in Figures 8 and 9. The leaf temperature was less than air temperature when the radiation intensity was zero or low, but it has become more than air temperature with higher radiation intensity. The trends are always in proportional relation with both of radiation intensity and transpiration rate. Therefore, it seems as if the accelerating effect of radiation on transpiration rate may be due mainly to the increase of the temperature of needles.

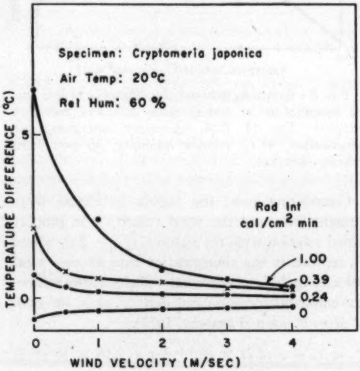

FIG. 9 – Relation between the difference of leaf and air temperature and wind velocity; Feb. 1 to Mar. 31, 1954, laboratory experiment

The relation between leaf temperature and wind velocity also resembled that of transpiration rate and wind velocity, as in case of *Myrica rubra*. It also seems probable that the transpiration rate follows the change of the leaf temperature.

Thus the trends show the close correlations between mean temperature of leaves, transpiration rate, and meteorological elements, and the relations between them follow regular trends.

Estimation of the total transpiration from a stand—According to the statistics during the period of recent 30 years in Shimonoseki, Japan, the mean meteorological conditions in August [*Tokyo Astronomical Observatory*, 1953] are: mean air temperature, 26.6°C; mean relative humidity, 80 pct; mean wind velocity, 3.5 m/sec.

It will not be the same in Namera National Forest. We have employed these values for the present in order to show how to estimate the total transpiration from a stand of *Cryptomeria japonica*, as there are no meteorological data in Namera National Forest. The intensity of radiation as 1 cal/cm²min was assumed.

The numerical values necessary to calculate the transpiration rate of *Cryptomeria japonica* under above meteorological conditions are: R = 1 cal/cm²min, H_r = 0.80, v = 3.5 m/sec, and e_s = 26.14 mmHg (at 26.6°C) [*Fowle*, 1934]. Substi-

TABLE 1 – *Comparison of the amount of water loss from surface of various types*

Type	Amount of water loss			Remarks
	per 4376 m²	per km²	per acre	
	ton/hr	ton/hr	ton/hr	
Stand of *Cryptomeria japonica*	1.80	411.32	1.66	Transpiration excluding evaporation from surface during August
Paddy field	1.06	242.22	0.98	Transpiration with evaporation from water-surface; mean value during August 1933
Water	0.16	36.56	0.15	Mean water temperature, 15.2°C
Water	2.20	502.72	2.03	Mean water temperature, 23.8°C
Grassland	0.37	84.55	0.34	Transpiration and evaporation; mean soil temperature, 12.5°C
Grassland	0.72	164.53	0.67	Transpiration and evaporation; mean soil temperature, 18.8°C
Wet soil	1.38	315.34	1.28	Perfectly wet soil; mean soil temperature, 18.6°C
Wet soil	0.76	173.67	0.70	When only thin surface layer was dried; mean soil temperature, 14.5°C
Wet sand	0.66	150.82	0.61	When only thin surface layer was dried; mean sand temperature, 23.6°C

tuting these values in (5), we have

$$T_{3.5} = 2.61 \text{ gr/hr per 100 gr of green leaf weight} \quad (6)$$

Accordingly, the total amount of transpiration per hour from this stand (4376 sq m; 1.1 ac) is calculated by (4) and (6) as

$$2.61 \times 10^{-5} \times 68914 = 1.80 \text{ ton/hour}$$

In order to compare this amount of water loss by transpiration with that of evaporation and transpiration from the surface of paddy field, water, grassland, wet soil, and wet sand, of the same area, that is, 4376 sq m, these materials (except paddy field) were filled into a culture dish, 11.7 cm in inner diameter and 2.7 cm in its depth, one by one, having previously poured in it an adequate quantity of water. This dish was buried at the center of a china vat, 36 cm x 28 cm x 4.6 cm in its dimensions, also filled with the same material in order to minimize the edge effect. The china vat with culture dish in its center was then placed in the wind tunnel and only this culture dish was weighed at an interval of 30 minutes under constant radiation intensity, air temperature, relative humidity, and wind velocity, of 1 cal/cm²min, 26.6°C, 80 pct, and 3.5 m/sec respectively. And the results were calculated in ton per hour per 4376 sq m.

These results are shown in Table 1. The amount of water loss from paddy field was calculated from the mean value of the experimental data during August 1933, by *Kano* amd *Matsuo* [1934; *Takata*, 1954].

Conclusions—The author has described the method of measuring the total leaf amount of *Cryptomeria japonica* and the derivation of the empirical formulas necessary to estimate the total transpiration of a stand or a forest of the same species.

The total leaf weight of a stand of 740 *Cryptomeria japonica* 45 years old, its total ground area amounting to 4376 sq m in Namera National Forest, Compartment 27, Yamaguchi District, Japan, was estimated at about 69 tons in 1951. The water loss by transpiration from this stand under such meteorological conditions as; radiation intensity, 1 cal/cm²min; air temperature, 26.6°C; relative humidity, 80 pct; wind velocity 3.5 m/sec; was calculated and estimated to be 1.80 ton per hour.

This amount was compared with the water loss from the surface of paddy field, water, grassland, wet soil, and wet sand, of the same area, that is, 4376 sq m. It was shown that the amount of water loss by transpiration from this stand (excluding direct evaporation from the Earth's surface) was larger than that of the various surfaces, except in case of water of 23.8°C.

It was thus shown that the amount of total transpiration from a stand or a forest under certain meteorological conditions can easily be estimated if the standard deviation of the breast-height diameters, the mean breast-height diameter, the number of trees in a stand or a forest, the constant proper to the species, and the relations of the transpiration rate to the intensity of radiation and the wind velocity are known. The discrepancy between the meteorological conditions in the open and that of the interior of a stand is not taken into account in this report. It should not be neglected in case a more accurate estimation is desired.

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A Method for Determining the Average Precipitation between Curved Isohyets*

GUY A. FRANCESCHINI

Abstract—A method is presented to enable the hydrologist to make more accurate computations, based on the isohyetal method, of precipitation volume over an area. Essentially, the method is concerned with determining the average precipitation value in areas between curved isohyets. The technique is developed for circular concentric isohyets but is extended to other cases. An overlay-nomogram is utilized for the computations.

Introduction—The volume of precipitation over the area between two isohyets is ordinarily assumed to be equal to the product of the enclosed horizontal area and the arithmetic average of the bounding isohyets. In the case of straight and parallel isohyets this assumption is correct. However, when the isohyets are curved, appreciable error may result.

Normally, because of the nature of precipitation measurements and the spottiness of data, no greater accuracy should be required of volumetric computations than that attained by using the arithmetic average. However, because of recent promising developments of radar techniques for determining total storm isohyets, it soon may be possible to determine a much improved areal distribution of precipitation for any storm [*Tarble*, 1957]. In anticipation of this development, it therefore seems necessary to consider a more refined method of computing the water volume. Consideration should take into account the effect of curvature of the isohyets on the proper average precipitation value used in the isohyetal method.

An approach to the problem is here considered. The simple case of circular concentric isohyets is treated, and a method is presented for the determination of a more realistic average precipitation value under this somewhat idealized condition. The method is then extended to non-circular and non-concentric isohyets.

Theory—Consider the hatched area A in Figure 1, bounded by two isohyets, R_a and R_b, and two radials, OP and OP', making an angle θ with each other such that they intercept portions of the isohyets that are circular and concentric. R_a and R_b are at distances a and b, respectively, from 0.

The volume of precipitation involved in this area A may be expressed as

$$V = \bar{R}A = \bar{R}(b^2 - a^2)\theta/2 \qquad (1)$$

where $\bar{R}$ is defined as the average precipitation over the area; θ is in radians.

The volume may also be expressed by the integral

$$V = \theta \int_a^b Rr\,dr \qquad (2)$$

where r is the radius to points included in area A, and R is the precipitation depth at similar points.

If we combine equations (1) and (2) and solve for $\bar{R}$ we get

$$\bar{R} = [2/(b^2 - a^2)] \int_a^b Rr\,dr \qquad (3)$$

Integration of (3) is possible if we know R as a function of r ($R \neq$ constant). Let us assume R to vary linearly as follows

$$R = R_a + (dR/dr)\,dr \qquad (4)$$

where $dR/dr = (R_b - R_a)/(b - a) = \Delta R/(b - a)$, and $dr = (r - a)$.

Substitution of (4) into (3) gives

$$\bar{R} = [2/(b^2 - a^2)] \cdot \int_a^b r[R_a + (r - a)\Delta R/(b - a)]\,dr \qquad (5)$$

Eq. (5) may be integrated directly, and upon simplification reduces to

$$\bar{R} = R_a + [1 + b/(b + a)]\,(R_b - R_a)/3 \qquad (6)$$

or

$$\bar{R} = R_a \mp ([1 + b/(b + a)]/3)\,|\Delta R| \qquad (7)$$

The minus sign is used when R decreases with increasing r, which is the usual case; the plus sign when R increases outward.

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* This is a contribution from the Department of Oceanography and Meteorology of the Agricultural and Mechanical College of Texas, Oceanography and Meteorology series number 103.

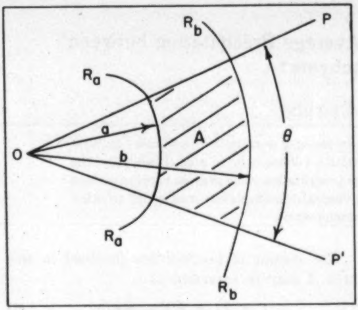

FIG. 1 – The horizontal area A between circular concentric isohyets

Eq. (7) may be simplified to

$$\bar{R} = R_a \mp f\,|\,\Delta R\,| \qquad (8)$$

where

$$f = [1 + b/(b + a)]/3 \qquad (9)$$

It will be noted that $|\,\Delta R\,|$ is the magnitude of the isohyetal interval. Should unit isohyets be drawn the average precipitation value $\bar{R}$ reduces to the sum or difference of the inner isohyet and the dimensionless factor f. The value of f can be quickly obtained by use of a nomogram which is explained in a later section.

The f factor—It may be instructive to consider (9) briefly in a somewhat different light for a better understanding of the construction and use of the nomogram.

If we consider the difference x between the radii of isohyets bounding an area, then

$$x = (b - a) \qquad (10)$$

Substitution of this value of x into the equation for f gives

$$f = [(3a + 2x)/(2a + x)]/3 \qquad (11)$$

In this form the value of f is seen to depend on the radius a of the inner isohyet R_a and the distance x between isohyets bounding the area considered.

The f values fall within the limits $0.50 < f < 0.67$. Table 1 shows the various values as a function of a and x.

The f-factor nomogram—Solutions for the values of f with concentric isohyets of different radii, a and b, are given by the f-factor nomogram (Fig. 2) which was constructed from values given in Table 1.

TABLE 1 – *The factor f for various values of inner radius a and difference x between inner and outer radius (b − a)*

a	x									
	1	2	3	4	5	6	7	8	9	10
0	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0.67
1	0.56	0.58	0.60	0.61	0.62	0.63	0.63	0.63	0.64	0.64
2	0.53	0.56	0.57	0.58	0.59	0.60	0.61	0.619	0.62	0.62
3	0.52	0.54	0.56	0.57	0.58	0.58	0.59	0.60	0.60	0.60
4	0.52	0.53	0.55	0.56	0.56	0.57	0.58	0.58	0.59	0.59
5	0.52	0.53	0.54	0.55	0.56	0.56	0.57	0.57	0.58	0.58
6	0.51	0.52	0.53	0.54	0.55	0.56	0.56	0.57	0.57	0.58
7	0.51	0.52	0.53	0.54	0.54	0.55	0.56	0.56	0.57	0.57
8	0.51	0.52	0.53	0.53	0.54	0.55	0.55	0.56	0.56	0.56
9	0.51	0.52	0.52	0.53	0.54	0.54	0.55	0.55	0.56	0.56
10	0.51	0.52	0.52	0.53	0.53	0.54	0.54	0.55	0.55	0.56

The nomogram consists of a series of arbitrary concentric circular arcs of different radii (a and b). Along the central vertical axis each arc is connected to others of greater magnitude by horizontal tangent lines. These lines are merely a device to connect one radius with another, that is, a with b, and represent the parameter x. Making the lines tangent was an arbitrary choice. The sloping lines emanating from the origin 0 are lines of constant f. The magnitudes of the f lines are indicated along the scale at the right. These are the only values involved in the computation. The values of a and b are automatically considered by superimposing the nomogram overlay on the isohyetal pattern so that isohyets and circular arcs coincide.

Use of the f nomogram—For practical purposes the nomogram is most useful when made up as a transparent overlay. Any convenient choice of concentric arcs may be included depending on the nature and size of the isohyetal pattern analysed. The areas to be considered are those having curved isohyets.

There are essentially three steps in the use of the overlay. (The section, *Comments*, will amplify these.)

(1) Select the radials so as to include similarly curved isohyets—circular and concentric.

(2) Place the nomogram over the region considered so that any two of its concentric arcs coincide simultaneously with the isohyets bounding the area within the radials.

(3) Read the value of f at the intersection of the line tangent to the arc coincident with the inner

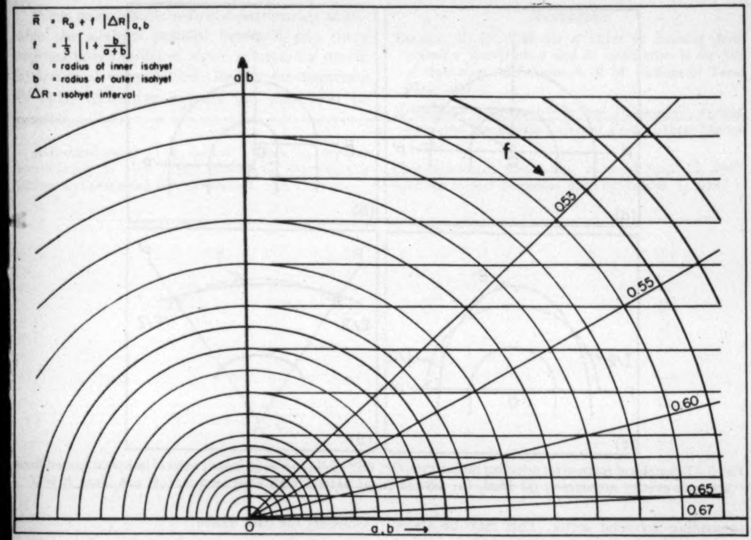

FIG. 2 – The f-factor nomogram for computing average precipitation depth between isohyets of interval Δ R

isohyet, and the circular arc coincident with the outer isohyet.

The value of $\bar{R}$ may then be obtained by using (8), $\bar{R} = R_a \mp f\,|\Delta R|$. This value of $\bar{R}$ then is substituted in Eq. (1), $V = \bar{R}A$, giving the volume of precipitation which has fallen in area A. It must be remembered, A is the horizontal area included by the bounding radials as defined in connection with Figure 1. The quantity A may be obtained either by planimeter or grid methods and should be done after the radials have been selected.

Comments—Since the quantity f, Eq. (11), involves like terms in both numerator and denominator, any map scale factor will cancel, and hence need not be considered. The nomogram therefore may be used directly on all charts of different scales. The only consideration required is of convenient size.

Note that any two isohyets may be considered simultaneously. They need not be of any fixed interval. (As will be seen later, they need not be circular nor concentric.)

In cases where circular and concentric isohyets do not coincide with arcs on the nomogram, intermediate coincident arcs may be interpolated. Further, the isohyets need not form complete circles. All that is required for the ideal case is that the curvature of the bounding isolines remain constant (see Fig. 3a). In regions where the curvature varies it may be possible to divide the area into smaller parts each of which meets the ideal requirement (see Fig. 3b). In any case the radials should be selected first to properly separate areas with different isohyetal curvature.

Although we have been considering a way to treat the simple case of circular isohyets we may apply the method, to a good approximation, to non-circular (elliptic, parabolic, and straight) isohyets. The procedure in these common cases is to first select the radials so as to eliminate straight and parallel isohyets, and include, if possible, those of similar curvature in each sector. The radials of adjoining sectors need not have a common origin but care must be taken to insure no region is excluded nor used in more than one computation. Next, treating each sector separately, select circular arcs on the nomogram which intersect isolines of the sector so that the area of the nomogram sector for each arc equals that of the cor-

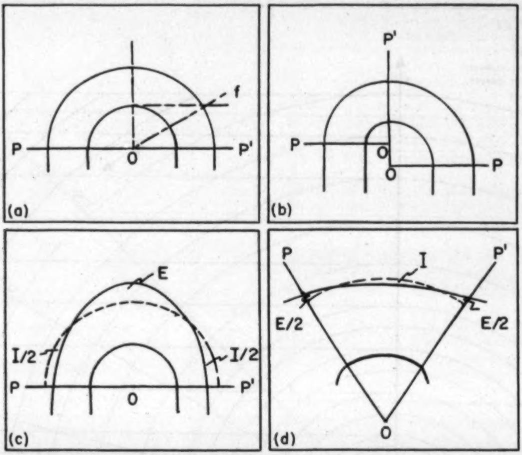

FIG. 3 – Examples of method for selecting radial lines, OP, OP'; solid curves represent pairs of isohyets; dashed lines are from overlay nomogram; (a) ideal; (b) asymmetrical pattern with ideal sectors; (cd) non-ideal, $E = I$

responding isohyetal sector. This may be stated another way. The arc selected should be area preserving, that is, it should exclude from its sector an area E within the isohyetal sector equal to the area I it includes from without the isohyetal sector. Figures 3c and 3d show a few such cases. Care must be used if the patterns are not symmetrical for then the equalizing of areas becomes less accurate. It may be that one of the isohyets is circular in which case the task is halved. Once the area-preserving arcs are selected the value of f will be given at the intersection of the inner arc tangent line, and the outer circular arc.

There are undoubtedly cases which are not amenable to the above considerations, that is, adjacent isohyets having opposite curvatures, and non-parallel straight lines. In such cases the arithmetic average is probably the best resort.

In cases where the curvature of the isohyets reverses sign, or the isohyets oscillate, the arithmetic average of the bounding isohyets may be used for the area included between radials which isolate one wave length of the oscillation, or some integral number of wave lengths. Experience in the use of the overlay will reveal other short-cut techniques and adaptations.

Conclusions—A numerical example will point to the advantage of using the f-factor nomogram. Consider the case where:

$$A = 500 \text{ mi}^2$$

$$R_a = 2 \text{ in}; \qquad R_b = 1 \text{ in}$$

$$b = 4a$$

The volume of water using the arithmetic average precipitation is

$$V = \bar{R}A = 1.5 \times 500 = 750 \text{ in mi}^2$$

Use of the nomogram gives $\bar{R} = 1.4$ in. The volume using this value is

$$V = \bar{R}A = 1.4 \times 500 = 700 \text{ in mi}^2$$

The difference in volumes, 50 in mi², is equivalent to 1.16×10^8 ft³ or about 8.69×10^8 gal, an appreciable amount for a small basin, although only about seven per cent of the total amount.

In general, since total storm isohyetal patterns consist of one or more centers of high precipitation (rather than low centers), values obtained by the suggested computations will be smaller than those computed using the arithmetic average precipitation. The greatest deviations will occur in areas where the inner isohyet has a small radius, and the distance between isohyets is large.

When more reliable isohyetal patterns are available the methods outlined here will give more representative values of water volumes for use in hydrological computations. Recent developments in radar techniques indicate this may soon be possible.

Acknowledgement—The author wishes to express appreciation to Mrs. Peggy Howell for drawing the figures and preparing the manuscript.

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The Thermal Regime of an Arctic Lake

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Abstract—Much of the Arctic coastal plain in Alaska is covered by shallow lakes. Those in the Barrow area, which are believed to be representative of most of the lakes in the coastal plain, are generally either two to three feet or six to nine feet deep. The shallow lakes can often provide a suitable summer water supply, but only the deeper lakes provide a significant water supply throughout the year.

The water in the individual lakes is in an essentially isothermal state during the ice-free period that lasts from late June until September. The maximum temperature recorded in a lake near Barrow in 1954 was about 12°C. When ice formation begins, the temperature of the body of water as a whole may be only a few tenths of a degree above 0°C. Once the lake surface is iced over, the water temperatures may rise rapidly as much as 2°C., apparently owing to radiated heat received through the ice. The heating is terminated by a sudden cooling that coincides with the covering of the ice by a thin blanket of snow. This cooling is followed in turn by a second warming of the bottom and near-bottom water that takes place gradually over a period of weeks. The bottom sediments beneath the lake are the source of heat. The magnitude of the second rise and the time during which it takes place depend on the distance from shore and the depth of water. A gradual cooling takes place during the balance of the winter. Permafrost underlies the shallow lakes but an unfrozen basin several hundred feet deep may extend beneath the deeper lakes.

Introduction—Lakes or drained lake basins may comprise locally from less than 25 pct to as much as 90 pct of the surface area of the Arctic coastal plain of Alaska [*Black* and *Barksdale*, 1949]. The lakes in the Barrow area (Fig. 1), which are believed to be representative except in areal extent of most lakes in the coastal plain, are either two or three feet or six to nine feet deep.

The lakes are important sources of water supply for the people in the area. Deep pockets in rivers can also provide an additional source of water in both winter and summer. Because of the considerable thickness of permafrost (as much as 1300 ft), no wells to date have provided usable water at Barrow, or have ever been drilled to my knowledge. *Cederstrom* [1952] has described limited supplies of ground water at Kotzebue and Point Hope but these places are south and west of the coastal plain and it is very doubtful that similar conditions would prevail near Barrow. The shallow lakes can often provide a limited suitable water supply during the summer but, once ice formation begins, the supply of water decreases rapidly and by midwinter they provide water only in the form of ice. Lakes more than six to seven feet deep do not freeze to bottom and can provide a limited water supply throughout the winter and a large supply in the summer.

The U.S. Geological Survey has studied the thermal regimes of several lakes in the Barrow and Umiat areas as part of a program of investigation of the distribution of and temperatures in permafrost in northern Alaska and because of the need for specific information on sources of water supply. Detailed studies were made from 1951 to 1955 in Fresh Lake (locally Imikpuk, which means 'big drinking water' in Eskimo). This lake is the nearest year-around source of fresh water to Barrow Camp which is situated on the ocean beach immediately west of the lake 3½ miles northeast of Barrow (Fig. 1).

Imikpuk Lake—Imikpuk Lake has an approximate area of 155 acres and at its closest point lies within about 400 ft of the Arctic Ocean (Fig. 2). The lake is elliptical in shape and its long dimension is approximately north-south. It can thus be considered typical of the lakes in this part of northern Alaska which generally have their long dimension oriented in a north-south direction [*Black* and *Barksdale*, 1949]. The deepest part of the basin, approximately ten feet, is west of the center of the Lake.

Imikpuk is separated from the ocean by a gravel beach with a maximum height of ten feet. This beach is normally sufficiently high to prevent any inrushing of ocean water during storms although some contamination did occur during an unusually severe storm in October 1954. The average water level of the lake is about two feet higher than that of the ocean; it had been assumed that the water remained fresh because the lake was separated from the ocean by a continuous impermeable

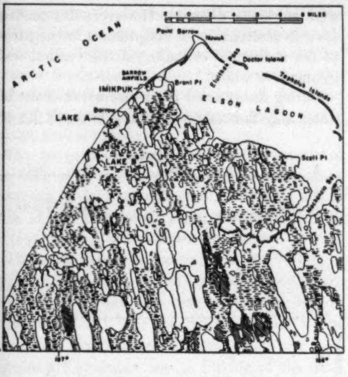

FIG. 1 – Numerous lakes and old lake basins dotting the Arctic coastal plain near Barrow, Alaska

permafrost barrier beneath the beach. Investigations by the U. S. Geological Survey indicate that there is a shallow frozen dam of varying thickness but that it does not extend to depths greater than 30 feet. There is in fact an unfrozen zone with a high saline content beneath the frozen beach gravels. This unfrozen zone is continuous with an unfrozen zone, also thought to have a high saline content, beneath the lake. It therefore seems that the fresh water in the lake is resting on brine-contaminated sediments whose pore water is not sealed off from the ocean. This condition should not endanger the existence of the lake as a source of fresh water, however; the only real danger to the use of the lake as a source of potable water, other than contamination by refuse, lies in the possibility that the ocean may breach the shallow permafrost dam during an unusually severe storm and that the lake will be converted to a lagoon. Several Barrow inhabitants say that one or two lagoons have been formed in this way within the last century and an interpretation of local geologic history suggests many others have had a similar history.

Techniques of observation—The measurements of the temperature in the lake during the winter were obtained by freezing multiconductor cables containing regularly spaced thermistors, [*Swartz*, 1954], into the ice and leaving these cables in place for periodic measurements through the season. Readings were usually obtained three times weekly although there were periods when readings were obtained at intervals as short as six hours or as infrequently as once a week. Tests based on the use of an ice-water bath for a standard indicate the accuracy for all measurements is better than 0.1°C, usually close to 0.03°C. The accuracy of the measurement of temperature change at any one thermistor is ±0.01°C.

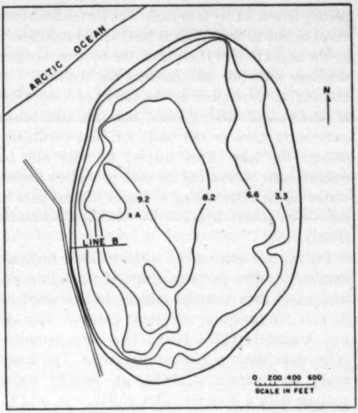

FIG. 2 – Bottom contours (in feet) of Imikpuk Lake near Barrow, Alaska [after *Comita*, 1953]

The measurements of the temperature of water during the summer were obtained by attaching multiconductor thermistor cables (painted white) to wooden poles that were shoved or driven into the lake-bottom mud and left in place. Some of these cables were left in place and frozen in an upright position for continued use during the winter.

A hole 200 ft deep (point A in Fig. 2) was drilled beneath the lake in the spring of 1953. Thermistor cables were installed and successfully read then and again late that fall.

A thermistor cable containing 27 regularly spaced thermistors was laid along the bottom of the lake from a point near shore to a point 546 ft from shore (line B in Fig. 2) in the fall of 1954. Periodic readings were obtained from this cable for a period of one year.

Temperatures during periods of open water—The ice in the lakes on the Alaskan coastal plain usually starts to melt during the first week of June. In the shallow lakes the ice may melt from the top without ever floating and the lakes may be completely free of ice by late June. The ice in the deeper lakes begins to float after it has melted sufficiently at the edges to free itself from the bottom. Surface drainage into the lake hastens the melting. The floating ice is subject to the forces of wind while it continues to melt; it often rams the lake banks sufficiently hard to roll back turf and eventually enlarge the lake. This floating ice may also be instrumental in creating the shelf or shallow underwater bench surrounding a deeper central part in lakes such as was described by *Black* and *Barksdale* [1949].

During the summers of 1951 to 1956 Imikpuk became ice free between July 17 and July 28. The water then warmed rapidly and attained its highest temperature sometime between July 30 and August 14 (1952–1955). The water temperatures then began a fluctuating decline. The maximum temperature in 1954, an usually warm summer with a thawing index of 933, was +12°C. (The thawing index is defined as the total cumulative (degree F) days above freezing for a thawing season [*Linell*, 1953].) The maximum temperature during 1955, an unusually cold summer with a thawing index of 310, was +8°C. The average thawing index at Barrow is about 600.

The water in Imikpuk is essentially isothermal both vertically (Fig. 3) and horizontally (Fig. 4) at any time during the ice-free period. Some indication of vertical temperature stratification in the upper foot of water in the lake has been noted (August 11 and September 17, 1954 in Fig. 3) on days when the temperatures of the air and water were markedly different. However, this tendency towards stratification is insignificant in comparison to the isothermal character of the vertical water column as a whole.

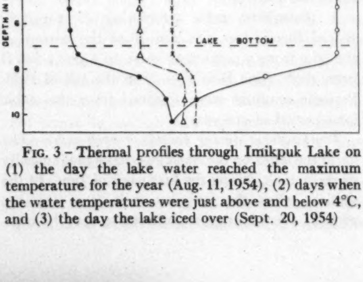

FIG. 3 – Thermal profiles through Imikpuk Lake on (1) the day the lake water reached the maximum temperature for the year (Aug. 11, 1954), (2) days when the water temperatures were just above and below 4°C, and (3) the day the lake iced over (Sept. 20, 1954)

During the summer the temperature of the lake water may fluctuate a degree or two per day and

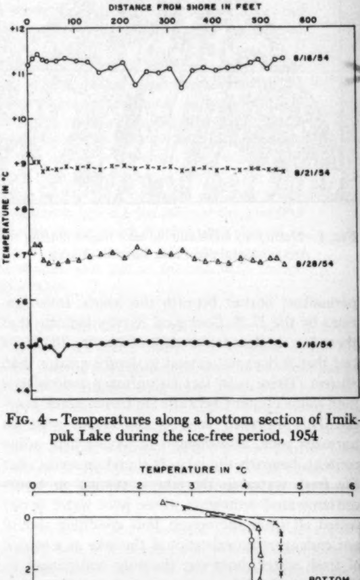

FIG. 4 – Temperatures along a bottom section of Imikpuk Lake during the ice-free period, 1954

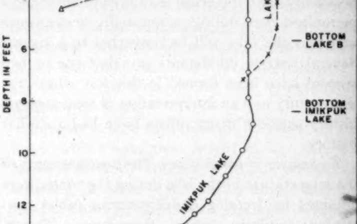

FIG. 5. – Thermal profiles through lakes of different depths near Barrow, Alaska, September 1, 1952

the fluctuation is always approximately the same for the entire column (see data for September 13, 17, and 20, 1954, Fig. 3) even though sometime between September 13 and 17 the water in the lake reached its maximum density and the direction of the thermal gradient in a stable water column was reversed.

The temperature of the mud in the bottom of the lake also fluctuates. However, there is a phase lag in the time of fluctuation and the amplitude of the fluctuation is rapidly damped with increasing depth beneath the lake bottom.

The temperature in the water on the bottom of Imikpuk is the same, within a few tenths of a degree Centigrade, at any one time during the ice-free period, (Fig. 4). The small irregularities in the horizontal temperature profiles along the lake bottom are probably due to sinking of the cable and the measuring elements into the mud, or to areas in which the bottom material has different radiative properties. As the vertical water column is also in an essentially isothermal state at any one time (as is verified by many sets of readings taken at several stations during the summers of 1951–1955), it has been concluded that the whole lake is in essentially an isothermal state at any given time during the ice-free period.

To determine if this isothermal condition prevailed in other lakes or was unique to Imikpuk, vertical thermal profiles through Imikpuk and two other lakes of different depths in the Barrow area were measured on September 1, 1952 (Fig. 5). Lake A and Imikpuk Lake are near the Arctic coast and probably subject to about the same weather conditions. Lake B, with a basin approximately the same depth as Imikpuk, is about six miles inland from the coast and should be less affected by the moderating influence of the ocean. Lake A is 2.6 feet deep and underlain by permafrost at a depth of less than five feet, whereas

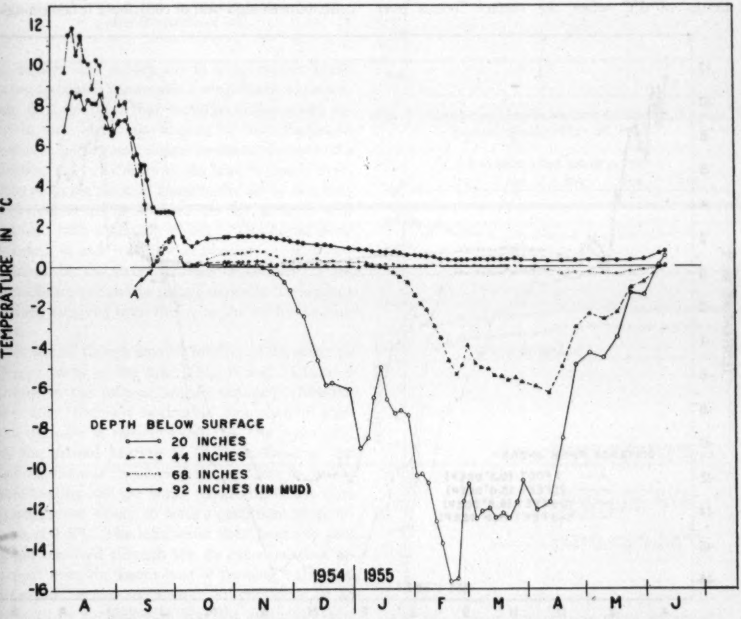

FIG. 6 – Time-temperature curves at several depths in Imikpuk Lake near Barrow, Alaska; lake 6 ft 4 in deep at this site

Imikpuk is 8.4 feet deep at the point of measurement and there is no permafrost within the first 190 ft under the deeper part of the lake. Despite these differences, the temperatures of the water in the three lakes were similar and each lake was in an isothermal state.

Temperatures during period of ice cover—A thin skin of ice may form on the fresh-water lakes in the Barrow area any time after September 1. The lakes usually ice over completely for the winter September 15–20 although open water remained until September 30 once during the six years of observation (1950–1955). As soon as the lake is iced over, freezing proceeds rapidly and the ice may be four to six inches thick within two weeks. Initially the ice freezes faster near shore giving the impression of an arch (possibly six inches at the edge and four inches 100 ft from shore) covering the water. However, as the winter progresses, the arch tends to disappear.

The temperature of the lake is within a few tenths of 0°C when the surface freezes over (September 20, Fig. 3). As soon as the lake is completely iced over the temperature of the water at all depths except near the freezing surface begins to increase rapidly (point A in Fig. 6). At the same time the temperature in the mud beneath the lake (Fig. 6, 92-inch depth) stops its rapid decrease and may remain virtually the same for approximately two weeks indicating a sharp decrease in the rate of heat loss from the sediments during this time. In the fall of 1954, the increase in the temperature of the lake was approximately 2°C. The maximum temperature was reached in 11 days (September 20 to October 1) and five days later the temperature returned to approximately that prevailing before the sudden rise. The rise seemed to be general throughout the lake. The possible sources of heat are the warmer sediments beneath the lake, bacterial action, or radiation. The warmer bottom sediments may contribute a minor amount of heat; however, the low thermal gradient and the length of time involved indicate that the sediments cannot contribute enough heat or contribute it fast enough

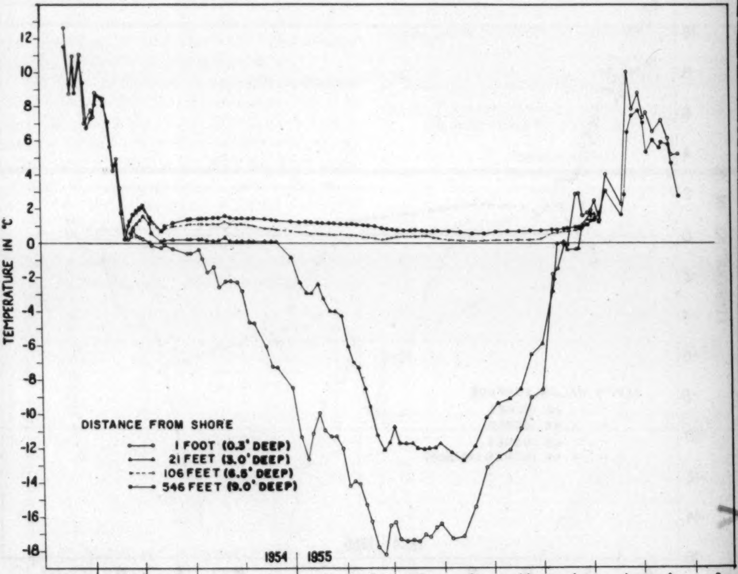

Fig. 7 – Time-temperature curves along bottom of Imikpuk Lake near Barrow, Alaska

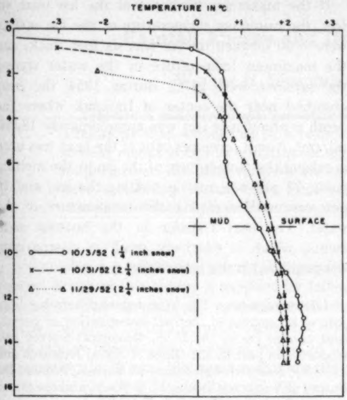

FIG. 8 – Thermal profiles through Imikpuk Lake showing second heating and cooling of bottom water after formation of ice

to explain this sudden rise in temperature. There is not too much known about weak bacterial action, but it is doubtful that bacterial action could account for a significant amount of heat. Radiation seems to be the most logical source of the heat; the heating starts as soon as the lake is frozen over, thus reducing the heat losses to the air by evaporation and stops as soon as the ice is fairly well covered with a blanket of snow. The initial snow blanket would reduce the amount of radiation received by the water through the ice and yet not be sufficiently thick to reduce radically the amount of heat escaping from the ice to the air by conduction.

A second though smaller heating of the water in deeper parts of the lake, (Fig. 6 and 7) from a source in the warmer bottom sediments beneath the lake, becomes noticeable immediately after the decrease in radiative heating. The magnitude of the second heating in Imikpuk Lake in the fall of 1954 was about one-half that from the radiative heating and the water required a longer time (about seven weeks) to reach a maximum temperature of 1.5°C. The lake water then began to cool (heat removed through the ice exceeded that received from the latent heat of freezing water and from the bottom sediments) and continued to do so until by the following May the maximum temperature in the lake was 0.6°C. During the latter period of heating and cooling the thermal profile through the water becomes a smooth continuous curve joining the temperature at the bottom of the ice with that in the bottom sediments (Fig. 8).

Prominent zero curtains are evident at depths of

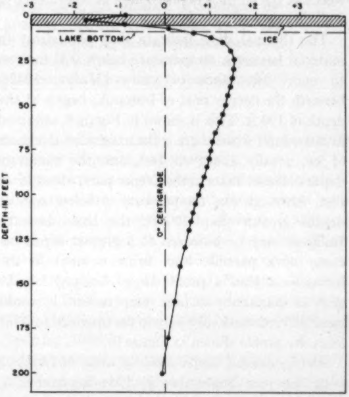

FIG. 9 – Geothermal profile beneath Imikpuk Lake near Barrow, Alaska, May 26, 1956

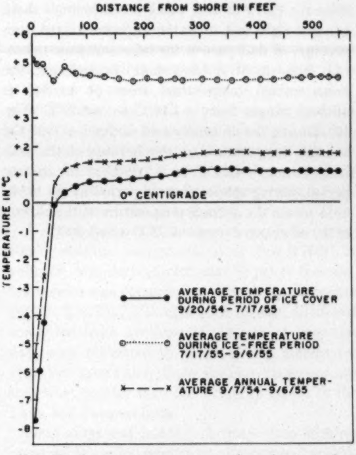

FIG. 10 – Average temperatures along bottom of Imikpuk Lake

20, 44, and 68 inches (Fig. 6) and at 21 feet from shore (Fig. 7). (The zero curtain is an interval of time during which the temperature remains constant as the chilling of water is temporarily compensated for by the latent heat of fusion [*Muller*, 1947].) The zero curtain persists for almost 10 weeks at the 68-inch depth. There is no evidence of a similar zero curtain in the spring (Fig. 7).

The thermal data indicate that permafrost (a material having a temperature below 0°C for two to many thousands of years [*Muller*, 1947]) beneath the deeper part of Imikpuk, begins at the depth of 190 ft. This is shown in Figure 9, obtained in late winter when there is the maximum thickness of ice, usually about six feet, and the minimum depth of liquid water in the deeper part, about three feet. Although the temperature is below zero at depths greater than 190 ft, the basin beneath Imikpuk may be unfrozen to a greater depth because of a possible high brine content in the formations. Had a profile been obtained for the time of maximum surface temperature, it would have differed markedly only in the upper 20 to 30 ft from the profile shown in Figure 9.

Average annual temperatures of water at Imikpuk—In the year September 7, 1954–September 6, 1955 the mean annual temperature at the bottom of Imikpuk ranged from —5.48°C at a point one foot from shore where the water was four inches deep to +1.79°C at a point 356 feet from shore beneath eight feet of water. However, if the temperature of that part of the lake that froze to bottom (edge to 61 ft from shore) is neglected, the mean annual temperature from 61 to 546 ft offshore ranges from +1.18°C to +1.79°C (Fig. 10). During the unusually cold summer of 1955 the average temperature at the bottom of the lake ranged from +4.29°C to +5.05°C in the ice-free period; during the ice-covered period in the 1954–1955 season the average temperature at the bottom of the lake ranged from —7.75°C to +1.20°C.

If the maximum thickness of the ice were six feet, the minimum temperature of the ice surface were —30°C when the ice was six feet thick, and the maximum temperature of the water during the summer were 12°C, during 1954 the heat absorbed near the center of Imikpuk where the depth is about nine feet was approximately 18,000 cal/cm². About seven per cent of the heat was used in raising the temperature of the ice to the melting point, 75 pct was used in melting the ice, and 18 pct was used in raising the temperature of the water. The heat transfer in the bottom sediments, which is relatively small in comparison, was neglected in this calculation.

Acknowledgments—The work reported here has been part of a program of thermal investigation of permafrost carried on by the U. S. Geological Survey and supported in part by the Office of Naval Research and its Arctic Research Laboratory at Barrow, Alaska, the Bureau of Yards and Docks, U. S. Navy, and the Snow, Ice and Permafrost Research Establishment, Corps of Engineers, U. S. Army.

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Rainfall Energy and Its Relationship to Soil Loss

WALTER H. WISCHMEIER AND DWIGHT D. SMITH

Abstract—A relatively simple procedure is presented for computation of kinetic energy of a rainstorm from information on a recording-raingage chart. An equation is developed describing rainfall energy as a function of rainfall intensity. The effects of rainfall energy and its interaction with other variables are evaluated in multiple regression analyses based on data representing four soil types. Application of this information to separate the effects of rainfall from those of physical and management characteristics in plot data is discussed briefly.

Soil erosion is a mechanical process that requires energy. Much of this energy is supplied by falling raindrops. The tremendous magnitude of the kinetic energy of rainfall is readily apparent from a few simple calculations. The dead weight of the water falling in 30 min. of a common thunderstorm in the cornbelt states may well exceed 100 tons on each acre. The billions of drops which comprise this 100-ton volume of water strike the soil, if unprotected, at an average velocity of nearly 20 mi/hr. The rainfall energy to be expended during the 30 minutes may well exceed two million foot-pounds per acre. If the rain is driven by violent winds, the energy of impact may be even greater.

In 1954, the Soil and Water Conservation Research Division of the Agricultural Research Service initiated a program to summarize all available runoff and soil-loss data on a national basis for further analyses. Studies on the project have pointed out that the accuracy of soil-loss prediction equations on an individual storm basis is considerably enhanced when a measure of rainfall energy is included as a variable, and that both the efficiency and the simplicity of such equations are further improved by terms measuring the interaction effects between variables. In this paper, a relatively simple procedure for computation of the approximate rainfall-energy value of a storm is presented, and the application of this information in more efficient estimates of expected soil loss is discussed.

Drop size—Studies of drop-size distribution of natural rainfall have shown a high degree of correlation between drop size and rainfall intensity. Size distributions of raindrops as a per cent of total volume were published by *Laws* and *Parsons* [1943] for intensities ranging from 0.01 to 6.0 inches per hour. These data are briefly summarized in Figure 1. The mean drop sizes, weighted by per cent of total volume, lie along the solid-line curve. The broken lines in the graph represent the boundaries of the 25–75 percentile and the 5–95 percentile ranges of drop size, respectively.

Measurements of raindrop records made on dyed filter papers for correlation with radar echoes were analyzed by *Marshall* and *Palmer* [1948] to give the distribution of drops by size. These distributions were in general agreement with those reported by Laws and Parsons. Information on raindrop size has also been reported by *Atlas* [1953], *Chapman* [1948], *Horton* [1948] and *Spilhaus* [1948b].

It is not expected that drops in sudden bursts of rain from a small cloud, or rains which are stopping and starting, would conform to any general size-distribution pattern. Data on the number of drops per unit volume for different types of rain indicate that the average volume per drop for a sudden rain from a small cloud or for the beginning of a short fall may be several times that in a general rain or a period of heavy continuous fall. This introduces a serious limitation to estimation of rainfall energy for such storms on the basis of intensity. Applied to rains of this type, soil loss prediction equations will, therefore, be less accurate. Fortunately, however, soil losses resulting from such storms generally comprise only a very small portion of the annual total.

A comprehensive summary of available drop-size information was presented by *Best* [1950a]. A value D_{50} was derived such that 50 pct of the rainfall volume was comprised of drops with diameters greater than D_{50}. Values of such median diameters computed from averages of six sets of drop-size data were tabulated by *Ekern* [1950]. Except for very low intensities, these median diameters are somewhat greater than the weighted means of the Laws and Parsons data.

Drop shape and velocity—A water drop with no appreciable motion relative to air assumes a spherical shape. However, a falling drop is deformed by flattening on the bottom and spreading sideways

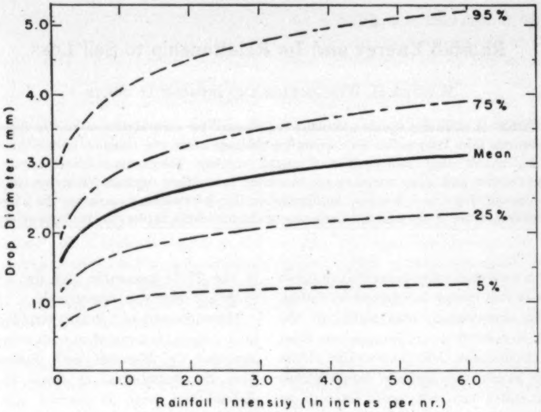

FIG. 1 – Drop-size distribution of natural rainfall

because of atmospheric pressure deficits developed on its top and sides and excess of pressure on the bottom. Terminal velocity is attained when the gravitational force on the drop is balanced by the drag of the air through which it is falling. Drops have been found to pass through a series of oscillations in shape while attaining terminal velocity. It does not appear unlikely that in simulated rain with a short fall, these oscillations may have a measurable effect on the stresses at impact. However, drops at their terminal velocity will usually have become stabilized in shape.

Published material on the terminal velocity of water drops includes reports by *Best* [1950b], *Blanchard* [1950], *Gunn* and *Kinzer* [1949], *Laws* [1941], and *Spilhaus* [1948a]. Gunn and Kinzer measured the terminal velocity of water droplets in stagnant air by inducing an electric charge and producing pulses on an oscillograph record. Their measurements are in good general agreement with values reported by Laws in 1941. Terminal velocities of drops of various sizes are plotted in figure 2, where equivalent drop diameter is defined as the diameter of a sphere of equivalent volume.

Rainfall energy table—If rainfall energy measurements are to be used extensively as a basis for more accurate estimation of rainfall erosion, a simple procedure for determining the kinetic energy of a rainstorm is required. Table 1 is presented to meet this need. Kinetic energies in foot tons per acre inch for natural rainfall at the various commonly experienced intensities have been tabulated.

The change in velocity corresponding to a one-unit change in drop diameter is much greater for the small drops than for the larger ones (see Fig. 2). Therefore, the mass and velocity of the median drop size substituted into the standard formula for

TABLE 1 – *Kinetic energy of natural rainfall* (*foot tons per acre inch*)

Intensity	Intensity, inches/hr									
	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
in/hr										
0	0	254	354	412	453	485	512	534	553	570
0.1	585	599	611	623	633	643	653	661	669	677
0.2	685	692	698	705	711	717	722	728	733	738
0.3	743	748	752	757	761	765	769	773	777	781
0.4	784	788	791	795	798	801	804	807	810	814
0.5	816	819	822	825	827	830	833	835	838	840
0.6	843	845	847	850	852	854	856	858	861	863
0.7	865	867	869	871	873	875	877	878	880	882
0.8	884	886	887	889	891	893	894	896	898	899
0.9	901	902	904	906	907	909	910	912	913	915
	0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
1	916	930	942	954	964	974	984	992	1000	1008
2	1016	1023	1029	1036	1042	1048	1053	1059	1064	1069
3	1074	1079	1083	1088	1092	1096	1100	1104	1108	1112
4	1115	1119	1122	1126	1129	1132	1135	1138	1141	1144
5	1147	1150	1153	1156	1158	1161	1164	1166	1169	1171
6	1174	1176	1178	1181	1183	1185	1187	1189	1192	1194
7	1196	1198	1200	1202	1204	1206	1208	1209	1211	1213
8	1215	1217	1218	1220	1222	1224	1225	1227	1229	1230
9	1232	1233	1235	1237	1238	1240	1241	1243	1244	1246

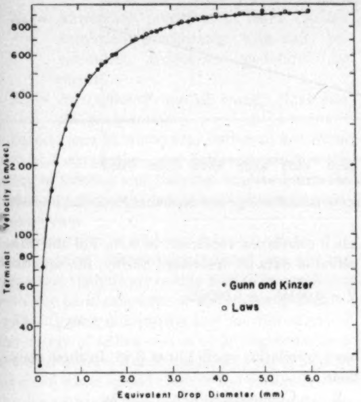

FIG. 2 – Terminal velocities of water-drops of different sizes in stagnant air

kinetic energy would yield results greater than the true energy value. The regression equation from which the values in Table 1 were derived is

$$Y = 916 + 331 \log_{10}X$$

where Y is the kinetic energy in foot tons per acre inch, and X is the rainfall intensity in inches per hour.

The equation is based upon the detailed drop size distribution data published by *Laws* and *Parsons* and the published terminal velocities plotted in Figure 2. It is an excellent least-squares fit to the data. Energy values in Table 1 for intensities greater than six inches per hour were extrapolated. In view of the clear trends in the terminal velocity and drop size distribution data, such extrapolation beyond the range of the data appears sound.

To compute the energy value of a rainstorm, Table 1 is used with the information available from a recording raingage chart. A tabular record of intensities, with the amount of rain falling at each of the successive intensity increments, is obtained from the recorder chart. The table is entered with the midvalue of a specific intensity increment. The corresponding energy figure from the table multiplied by the inches of rain falling at this rate describes the energy value of that increment of the storm. These partial products are accumulated in a desk calculator to obtain the total energy value for the storm. Intensity intervals should not be large enough to average widely differing rainfall rates. Such average intensities would result in low computed values of kinetic energy.

Evaluation of the effects of rainfall characteristics—It is apparent to the observer that two rainstorms of equal total amount falling on the same field and on comparable surface conditions often produce widely differing soil losses. In order to analyze and solve erosion problems, it is necessary to know which characteristics of rainfall are responsible for such differences, and how and to what extent erosion is affected by each. This problem was approached primarily on a mathematical basis through multiple correlation analysis.

A large number of runoff and soil-loss data on an individual storm basis are available from plots in continuous fallow, with cultural operations identical to those on the corn plots, and kept free of vegetal cover throughout the period of study. These data lend themselves to a study of rainfall effects undisturbed by differences in cover, amounts of organic matter in the soil, or other management practices. Availability of an electronic digital computer for the studies made it possible to compute multiple regression equations of soil loss on as many as 19 variables, simultaneously. Special emphasis was directed toward evaluation of effects of interactions of the variables. Data employed in the studies were from several major soil types and included variations in precipitation patterns. The coefficient of determination, which is the percent of total storm-to-storm variation in soil loss explained by the particular factor, was used as a measure of the degree of influence of that factor on soil loss.

The absolute values of the effects of the various rainfall characteristics vary with soil type and slope. However, the relative rank of the specific factors does not appear to differ for the soils and slopes included in the study.

Numerous combinations of rainfall characteristics, interaction effects, and indices of antecedent moisture and soil compaction were investigated in exploratory studies. The best single variable found for prediction of soil loss from cultivated fallow soil is the product of the total rainfall energy of a storm and its maximum 30-minute intensity. This product term measures the interaction effect of the two rainfall characteristics. It will be referred to hereafter as the $E \times I$ variable.

The regression line is plotted in Figure 3 for a

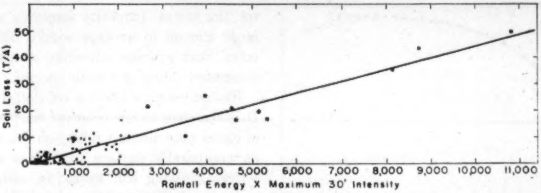

FIG. 3 – Individual-storm soil loss is a function of the product of rainfall energy and maximum 30-minute intensity

ten-year record, exclusive of the rough-plow winter period, on Shelby soil with a slope of eight per cent. The unit of the $E \times I$ variable on the horizontal axis is energy in foot-tons per acre-inch times maximum 30-minute intensity in inches per hour. Rains of a half inch or more, and smaller rains which resulted in measurable runoff, were included in the analysis. The solid block at the origin represents 60 observations. It is apparent that points representing storms with negligible soil losses were successfully concentrated near the origin when related to the $E \times I$ variable. The analysis indicates 95-pct confidence that the slope of the true regression line lies within the narrow band of 0.0042 to 0.0047.

In each of the five sets of data analyzed, the single $E \times I$ variable accounted for a greater portion of the total soil-loss variation than did a multiple regression on the five variables: rainfall amount, maximum 5-, 15- and 30-minute intensities, and antecedent precipitation. Mathematically, this very highly significant interaction of rainfall energy with maximum intensity means that the rainfall energy-soil loss relationship for a storm with any specific maximum 30-minute intensity is quite different from the energy-soil loss relationship for a storm with some other 30-minute intensity level. The values of some of the significant terms and combinations as soil-loss predictors are compared in Table 2.

The $E \times I$ interaction term is outstanding as a common denominator for rainstorm classification on the basis of erosion-producing capacity. Little, if any, accuracy is added by including rainstorm characteristics other than total energy in the equation. Efficiency of the prediction equation is improved, however, by the additions of rainfall energy and indices of soil moisture and compaction. For ten years of Shelby data exclusive of the winter period, the equation

$$Y = 0.00163X_e + 0.00389X_i + 0.0622X_a + 0.438X_p - 2.46$$

has a correlation coefficient of 0.96. For the same period of data on desurfaced Shelby, the equation

$$Y = 0.0026X_e + 0.0024X_i + 0.0517_a + 0.2330X_p - 2.93$$

has a correlation coefficient of 0.93. In these equations

Y = Computed soil loss, tons/ac
X_e = Kinetic energy of the rain in foot tons/ac.
X_i = $E \times I$

TABLE 2 – *Per cent of total storm-to-storm variation in soil loss explained (R^2) by the designated variables in regression equations*

Variables in regression equation	Soil type and number of storms in analysis[a]					
	Shelby[b] 138		Shelby 207	Shelby subsoil[c] 207	Marshall subsoil[c] 131	Fayette 144
	σ^d	R^2	R^2	R^2	R^2	R^2
Rainfall amount	4.0	73.0	68.3	64.6	38.7	42.2
Rainfall energy	3.3	81.7	78.2	73.9	54.9	61.6
Max 15-min intensity	5.8	43.4	40.9	25.7	50.4	65.5
Max 30-min intensity	5.1	56.2	59.8	35.1	56.0	79.9
Three variables[e]	3.6	78.6	73.8	67.6	66.2	82.6
$E \times I$ alone	2.5	89.2	81.7	75.6	70.7	88.0
$E \times I$ with 3 others[f]	2.2	92.1	85.8	80.2	78.6	88.3

[a] Shelby data include 10 yr of record on 8 pct slope; Marshall, 7 yr on 9 pct slope; Fayette, 6 yr on 16 pct slope.

[b] Shelby plots were fall plowed. The 138 storms exclude the rough-plow winter period. Other four groups include data for entire year.

[c] Seven inches topsoil mechanically removed.

[d] Standard error of estimate for the 138 storms in first R^2 column.

[e] Rainfall amount, max 15-min intensity and max 30-min intensity combined in multiple regression.

[f] Rainfall energy, $E \times I$, antecedent precipitation index, and total rainfall energy since last tillage operation.

X_p = Antecedent precipitation index (30-day antecedent precipitation with daily between-rain reductions modulated by season).

X_e = Accumulated rainfall energy since last tillage operation.

Inaccuracies in wintertime indices of soil moisture and compaction, and failure to measure the effect of freezing and thawing, tend to lower the estimating efficiency of an equation based on year-around data.

Interpretation of mathematical relationships—The mathematical relationships pointed out by the regression analysis are readily seen to be consistent with the basic principles of the erosion process.

The erosive actions of water are the effects of the energy of falling rain or of flowing water over the land surface. Runoff takes the form of shallow layers of water spread more or less uniformly over the land surface, and of channelized flow concentrated into defined watercourses. The former, coupled with raindrop action, produces sheet erosion. The concentrated scouring action of the channelized flow causes rill and gully erosion.

Sheet erosion is a function of rainfall characteristics, although the magnitude of the effects varies with soil condition, slope, cover, and management practices. It involves detachment of soil particles and transportation of the detached particles from the plot or field. Much of the raindrop energy may be expended in puddling and sealing of the land surface and in direct compaction of the soil. This results in increased runoff and intensification of rill erosion.

Splash erosion occurs whenever raindrops of sufficient size strike moist, unprotected soil as photographed in Figure 4. This results in a leveling of the surface and, on sloping land, in a gradual movement of surface particles down the slope. This type of erosion is not immediately measured, but may influence the amount of soil removed from the plot by a subsequent runoff.

When rainfall intensity exceeds the infiltration rate plus surface detention, excess water moves downhill, thus providing transportation for many of the detached soil particles that would not otherwise move off the plot. The velocity attained by the flowing water is a function of its depth and amount of vertical fall. Its silt-carrying capacity increases exponentially with the increasing velocity. Not only soil detached by the raindrops, but also additional soil detached by the flowing water, is carried from the field in increasing amounts as the depth of flow increases.

FIG. 4 – A raindrop striking moist soil bursts upwards and outwards, carrying pieces of soil with it (USDA-SCS photo by U. S. Navy Bureau Yards & Docks, Nov. 1949)

Depths attained by sheet flow under normal field conditions usually do not exceed a small fraction of an inch. The energy imparted by raindrop impact contributes greatly to erosion by such shallow flows. The direct splash action is reduced, but the energies of the falling drops are transferred to the surface flow in the form of turbulence and help to detach soil and to hold detached materials in suspension.

The $E \times I$ interaction variable appears to be a good measure of the combined effects of (a) the decreasing infiltration rate during a rain, (b) the geometrically increasing erosion effect of surface flow, and (c) the protection against raindrop splash which is afforded by the film of flowing water. A storm with rainfall energy per acre equivalent to that of an average rain but with very low maximum intensity would have an $E \times I$ value low enough to predict no soil loss in spite of the energy value. If the low-intensity rain lasts long enough, the infiltration rate may finally become low enough for runoff to occur. This would show up in the prediction equation by a sufficiently increased total rainfall energy to make the $E \times I$ product term large enough to predict soil loss. Another rain, with much smaller amount and total energy than the one just described but falling at a high intensity, may produce a comparable soil loss. Similarly, the magnitude of the product of a low energy value and a high intensity may be comparable to that of one with high energy and low intensity. In the case of a large rain at high intensity, the increased soil-detaching and soil-carrying capacities of the turbulent flow are described by the very large product of the two high components of the $E \times I$ term.

The interaction of energy with 15-minute maximum intensity is also highly correlated with soil loss but not so highly as the interaction with the 30-minute intensity.

The antecedent precipitation index in the equations affords a measure of the starting point on the time-infiltration rate curve.

The fourth variable in the equation, total rainfall energy since last cultivation, provides a measure of the effects of soil compaction, reduction in surface detention due to leveling of the surface by splash erosion, and sealing of the land surface.

An important part of the soil-loss variation not explained by the four variables in the erosion equation previously described is probably the result of wind effects. Increases in energy of impact due to driving winds were not included in the rainfall energy table. They probably account for some of the underestimated soil losses. Wind direction relative to the direction of land slope could affect the accuracy of soil loss prediction in two ways. In the first place, the detaching ability of the rain drops would be influenced by the angle of impact. Secondly, for a specific rain intensity measured in a vertical raingage, the energy of impact per unit area of land surface would not be the same for a rain driven by the wind in the direction of a rather steep land slope as for a similar rain in the opposite direction. Changes in wind direction during a rain probably tend to balance out these effects in many storms. However, when a strong wind holds a constant direction throughout the period of rain, deviation in actual rainfall energy from the computed amount could have a significant effect on soil loss. Related wind data are not available to test the importance of these hypotheses.

Applications of rainfall energy information—The preceding analyses indicate that, with factors other than rainfall held constant, soil loss per unit area from an individual storm varies as the product of rainfall energy and maximum 30-minute intensity. This fact has several valuable applications.

The ability to predict soil loss is improved by this more efficient measure of the effect of rainfall characteristics. The cost of computing multiple regression equations is gratifyingly reduced by the fact that one variable affords more information than four or five independent variables which would otherwise need to be included in the equation.

The accurate classification of rainstorms according to their soil-eroding potential is greatly facilitated by these findings. This will be a very convenient tool in analysis of accumulated data for the effects of slope, cover, and management effects.

Accurate evaluation of the erosivity of different soils has long been a problem to the application conservationist. The problem has been intensified by the fact that soil-loss data recorded at widely different locations had to be combined in efforts to evaluate these factors. Soil effects were confounded with the effects of differences in rainfall. It will now be possible to separate these effects and to add the rainfall factor to the slope-practice technique of applying conservation practices to the land. This will materially improve the accuracy of the method.

Some of the factors in current use for desribing cover and management effects are based on seriously limited available data. These can now be evaluated with greater confidence by considering the severity of the storms experienced in the brief periods of measurement as compared with long-run expectations.

Better measures of rainfall effects and soil-erodibility factors, used with soil classification data and Weather Bureau records, will increase the accuracy and degree of confidence with which research data may be adapted to other localities.

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Some Methods of Alleviating Surface Clogging in Water Spreading with Emphasis on Filters

LEONARD SCHIFF AND CURTIS E. JOHNSON

Abstract—Methods of preventing or alleviating clogging of soil pores when spreading water on soil surfaces or injecting water into aquifers for recharge are discussed. Observations of methods such as suction cleaning or scraping to remove clogging materials and restore the infiltration rate in some installed systems are pointed out. Certain past experimental work on the subject is reviewed.

Of various filter materials used in infiltrometers at Bakersfield, sand ranging in size from 0.5 to 1.6 mm maintained a higher infiltration rate than ⅛ or ¼ inch pea gravel or the existing aquifer material. Information is given on particle size distribution of both the filter and aquifer materials. Head losses due to filters and within the underlying aquifer are shown.

Introduction—Artificial ground-water recharge is accomplished by spreading water over land surfaces or injecting water into aquifers through shafts, wells, pits, or trenches. The permeability of the soil surface and subsurface soil down to the ground-water table controls the rate of recharge. The permeability of soil varies with texture and structure of the soil, being greater for coarse textural classes and better soil structure. Organic matter contained in the soil and vegetative cover affect soil structure and amount and size of pores, particularly in the fine- to medium-textured soils.

Research in ground-water recharge is concerned with soil and water treatments which increase the size of and stabilize the soil pores. It is concerned also with preventing or alleviating clogging of pores which can take place during recharge. By increasing the rate of infiltration, more water can be added to the ground-water reservoir in a given time or the area required for recharge can be reduced. Spreading on smaller areas provides better control in replenishing subsurface waters where desired.

Swelling of soil colloids with wetting is inherent in soils and depends largely on the amount and kind of colloidal material. Clogging caused by soil slaking and dispersion can be a result of unstable structure of the soil. This condition often occurs in soils of low organic-matter content. Low permeability caused by dispersion and loss of structure is a characteristic of soils having a high exchangeable sodium percentage. This may be due to existing conditions or may be a result of spreading waters of high sodium percentage. Some dispersion and break-down of surface soil structure can be caused by the physical force of the water as it is spread over the soil surface. Soil clogging may occur also due to microbial activity and the resulting accumulation of slimes, gums, gases, and microbial tissue within the soil pores.

This paper deals expressly with clogging of the soil surface which results from deposition of silt and smaller size particles carried into the area with the spreading water. These soil deposits accumulate more rapidly when water is injected for recharge since large quantities of water are passed through a relatively small area as compared to surface spreading.

Previous work—*Mitchelson* and *Muckel* [1937] have shown the value of selecting the upper portions of alluvial fans for spreading as represented by the debris cones at the mouths of canyons in Southern California. Coarse-textured soils on such locations have high permeability. Flows laden heavily with sediment have been bypassed to prevent severe reduction in infiltration rate due to surface clogging. Early observations indicated recovery in infiltration rate when a drying period followed a wetting period during which some sediment was deposited.

Richter [1955] shows that infiltration rates are lower on finer textured soils than on the coarser textured ones on spreading areas in California. The average infiltration rate for a water-spreading season of several months ranges from 4.2 ft/day for a coarse-textured soil to 0.46 ft/day for a fine-textured soil. However, infiltration rates averaging 3.6 ft/day have been maintained for seasons of several months over a period of several years on a fine sandy loam with a good native cover at the Saticoy Spreading Grounds, Ventura County, California. The grass cover at Saticoy maintains an open, friable surface soil of good structure even though water with a turbidity up to 575 ppm of sediment is spread. Water is bypassed when it exceeds this turbidity. Observations by the Los

Angeles County Flood Control District indicate that routing water through settling basins prior to spreading to remove some sediment and growing native vegetation in spreading basins to deposit sediment have increased infiltration rates.

Schiff [1955] has observed that soil treatments with vegetation, organic matter, and chemicals resisted clogging in that order. Percolation rates of less pervious subsurface layers appeared to limit further increases in infiltration rate. High injection rates are maintained in wells along the coast at Manhattan Beach in Southern California by using chlorinated water, free from suspended solids. Chlorine is used to prevent sealing by microbial activity. The high cost of clear chlorinated water can be justified in this case since the system of injection wells protects an inland ground water basin from sea-water intrusion.

Because limiting subsurface layers exist in various areas, injection methods employing shafts, pits, and trenches have been investigated. Surface and subsurface soil layers of low permeability have been removed, which permitted high heads of water to contact aquifers of high permeability. *Schiff* [1956] has shown that infiltration rates as high as 60 times that obtained by surface spreading have been achieved by injection methods. However, sediments brought in by the river water cause clogging and periodic cleaning is required. Sediment deposits are removed by scraping. Benefits from the water in any area must be weighed against costs of water, construction, maintenance and land.

Water delivered to basins on Long Island, New York has recharged ground water at a rate of 3 ft/day. Water meandering in canals over a portion of 80-acre Rohrer Island, Dayton, Ohio, has recharged ground water at a rate of 107 ac ft/day. At Bakersfield, California, a $\frac{1}{3}$-acre narrow trench infiltrated as much water over a comparable period of a few months as surface spreading on four acres of land.

Suter [1956] has shown that, at the $\frac{1}{7}$-acre Peoria Pit in Illinois, injection rates increased from an average daily volume of 3.2 to 9.5 ac ft/day when the sand filter over the aquifer was replaced with $\frac{1}{4}$ inch pea gravel. The filter has been effectively cleaned by suction.

A $\frac{1}{10}$-acre pit at Bakersfield was excavated through six feet of relatively impervious material (Fig. 1). This pit extended three feet into an 8-ft lens of coarse sand. It exposed $\frac{1}{20}$-acre of sand aquifer. Using river water, the injection rate dropped from a volume of 2 to 1.2 ac ft/day in 82 days. The $\frac{1}{4}$ inch pea-gravel filter was not effective, and clogging deposits on the sand aquifer beneath the filter on both the bottom and sides of the pit were removed by scraping with hand shovels to restore the infiltration rate. Mechanical analysis of a surface crust deposited in the pit showed that 81 pct of the material was clay.

Purpose of experiment—The remainder of this paper deals with an experiment to find filter materials that will sustain higher infiltration rates of aquifers. Apparently a filter material is needed that will cause sedimentation through a depth of the filter and thus retain sufficient porosity to sustain reasonably high infiltration rates during a spread-

FIG. 1 – Infiltration pit, Bakersfield, California, $\frac{1}{10}$-acre in area, which exposes $\frac{1}{20}$-acre of sand aquifer six feet beneath relatively impervious surface soil

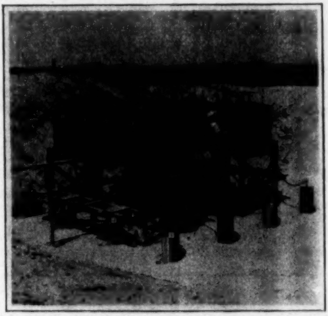

FIG. 2 – Arrangement of sixteen infiltrometers equipped with manometers to register head losses in filters and underlying aquifer material

ing season. The depth should be such as to permit cleaning by suction or by scraping at a reasonable cost. (The cheapest solution in some areas may be to inject water directly on an aquifer and clean by more frequent scraping than a filter may require.)

Procedure—Figure 2 shows 16 manometer-equipped infiltrometers with supply tanks located in a pit excavated to a depth of six feet to reach aquifer material. The aquifer material exposed is similar to the material in the 1/10-acre Bakersfield infiltration pit nearby, described above. The infiltrometers are three feet long and one foot in diameter. They were driven one foot into the aquifer material. Each infiltrometer is supplied with water from a storage drum. Surface head or depth of water in each infiltrometer is regulated by a float-controlled valve within the infiltrometer. The drums are supplied with water from a nearby ditch. There is a continuous supply of water to the infiltrometers at all times. Infiltration rate in a given infiltrometer is obtained by shutting off the water supply to the drum and measuring the rate of change of volume of water within the drum. The supply to the drum is turned on before the drum runs dry, thus maintaining a constant head of water within the infiltrometer. Kern River water is used for all runs. A run is considered to be a constant application of water over any period of time. Information is obtained on suspended solids and temperature of the water within the infiltrometers.

Filter materials 0.2 foot in depth were placed over the aquifer material. These materials included sand ranging in size from 0.5 to 1.6 mm, ⅛-inch pea gravel, and ¼-inch pea gravel (similar to the filter material used in the 1/10-acre pit).

Four infiltrometers containing aquifer material had no filters and are referred to as the controls. Table 1 shows a particle size analysis for the aquifer material for five depths at three locations. Table 2 shows a particle size analysis of all filtering materials.

Three runs were made. During the first and second runs, all filtering materials and the controls were replicated four times in a latin square design. During the third run, the sand filter and the con-

TABLE 1 – *Mechanical analysis of aquifer material sampled prior to the infiltrometer runs in the pit, Bakersfield, California*

Location	Depth	Particle size								
		>3 mm	2–3 mm	1–2 mm	0.5–1 mm	0.25–0.5 mm	0.1–0.25 mm	0.05–0.1 mm	0.002–0.05 mm	<0.002 mm
	ft	pct	pct	pct	pct	pct	pct	pct	pct	pct
1	0.0–0.01	2.4	6.9	27.7	35.9	17.7	6.9	1.2	0.3	1.0
1	0.1–0.2	4.3	8.3	25.5	36.0	17.5	4.2	1.5	0.4	2.3
1	0.2–0.4	3.9	7.2	21.4	37.8	22.1	3.8	1.2	0.3	2.3
1	0.4–0.7	7.0	9.8	25.0	31.0	20.1	3.3	1.6	0.2	2.0
1	0.7–1.0	4.9	13.5	31.6	28.1	16.3	2.8	0.9	0.2	1.7
4	0.0–0.01	0.8	2.8	21.7	40.9	26.1	4.4	0.9	0.1	2.3
4	0.1–0.2	1.1	6.2	28.6	37.3	20.4	3.7	0.5	0.1	2.1
4	0.2–0.4	8.9	14.9	28.3	27.3	14.7	2.9	0.7	0.2	2.1
4	0.4–0.7	9.5	13.4	29.8	27.4	14.8	3.2	0.2	0.1	1.6
4	0.7–1.0	5.8	11.5	33.0	32.6	13.3	2.0	0.4	0.1	1.3
10	0.0–0.01	6.6	10.3	26.2	23.8	20.9	7.9	1.9	0.3	2.1
10	0.1–0.2	4.4	10.2	25.8	25.0	22.4	7.8	1.8	0.4	2.2
10	0.2–0.4	3.3	8.6	26.8	29.2	19.2	7.5	2.8	0.2	2.4
10	0.4–0.7	5.7	8.2	24.6	31.0	20.7	5.3	2.1	0.3	2.1
10	0.7–1.0	4.1	8.4	26.8	35.0	16.5	3.3	3.2	0.2	2.5

TABLE 2 – *Mechanical analysis of the various filter materials after washing*

Filter material	Particle size							
	>5 mm	3–5 mm	2–3 mm	1–2 mm	1–1.651 mm	0.833–1 mm	0.5–1 mm	0.5–0.833 mm
	pct	pct	pct	pct	pct	pct	pct	pct
Sand	0	0	0	. . .	60.0	27.7	. . .	12.3
⅛-inch pea gravel	0	51.3	31.4	13.9	. . .	. . .	3.4	. . .
¼-inch pea gravel	55.0	44.8	0.2	0	0	0	0	0

trol were replicated four times. For the first run, the filter material was washed and dried and placed within the infiltrometers to a depth of 0.2 foot. For the second run, all filter materials used in the first run along with the aquifer material to a depth of 0.2 ft were removed and discarded. The infiltrometers were then driven 0.2 ft deeper into the aquifer material, and washed and dried filter material was placed in infiltrometers to a depth of 0.2 ft. The first and second runs were identical in design. For the third run, the above procedure was followed except that sand filter material was placed in the four infiltrometers used as controls (no filters) during the first and second runs, and the four infiltrometers from which the sand filters had been removed were used as controls. This tended to eliminate the possibility that differences were due to location.

A surface head or depth of water of 1.9 ft was maintained on the surface of the aquifer material during all runs. Losses in hydraulic head at the bottom of each filter and 0.1, 0.2, and 0.4 foot beneath the surface of the aquifer material were determined with manometers (Fig. 3).

Results and discussion—Table 3 shows the effect of the different filter materials on the infiltration rate of the aquifer material. Statistical analysis showed that the variance due to location of infiltrometers (columns and rows in the latin square design) is similar and non-significant. Increases in infiltration rate with the sand filter compared to the aquifer material without a filter are significant at the five per cent level during the first and third runs and at the one per cent level during the second run. In all tests, the coarse sand was the most effective in sustaining increased infiltration rates, whereas the ⅛-inch pea gravel was significantly effective in only the second run, and the ¼-inch pea gravel gave no significant improvement.

Hydraulic head losses occurred in the sand filters during the first and second runs averaging 0.05 and 0.02 ft respectively. Measurable head loss did not occur in the ⅛-inch and ¼-inch pea gravels. Average hydraulic head losses, infiltration rates, and hydraulic conductivities occurring in the aquifer material within the 0–0.2 ft depth with no filter and with a sand filter during the third run are shown in Table 4.

The data indicate more rapid clogging occurred in the aquifer material which had no filter than in the aquifer provided with a sand filter. No pressure greater than atmospheric was recorded at the 0.2-ft aquifer depth after eight days of run on the aquifer without filter material. This showed that the maximum hydraulic head (2.1 ft due to position) had been lost. At this time, 1.44 ft of head had been lost in the aquifer covered by the sand filter, and the maximum head was not lost until the 19th day.

Table 5 shows suspended solids contained in the water in the infiltrometers on various dates. The large range in suspended solids is due to maintenance operations in canals and to storms

TABLE 3 – *Infiltration rate in feet per day for infiltrometers containing various filter materials, Bakersfield, California*

Filter material	First run[a]	Second run[b]	Third run[b,d]
	Average rate	Average rate	Average rate
	ft/day	ft/day	ft/day
None	23.2	4.7	27.4
Coarse sand	43.0[e]	27.6[f]	44.9[e]
⅛-inch pea gravel	23.3	8.2[e]	...
¼-inch pea gravel	19.4	6.3	...

[a] Eighteen-day run.

[b] Filter material removed, top 0.2 ft of aquifer removed, infiltrometers driven in 0.2 ft deeper, 0.2 ft of clean filter material applied prior to run.

[c] Sixteen-day run.

[d] Forty-eight-day run.

[e] Significantly different from control at the five per cent level.

[f] Significantly different from control at the one per cent level.

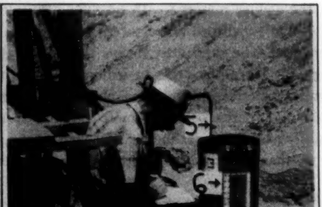

FIG. 3 – Representative infiltrometer showing water supply line and float control (5) and manometer tubes (6); the height of water in the manometers is indicated by a black band on each manometer tube and can be read directly against the scale painted on the infiltrometer

that vary considerably in intensity. Generally, turbidity is not high. However, there are periods during which suspended solids are high enough to cause clogging, particularly in injection spreading where the cumulative effect of the suspended solids becomes more rapidly detrimental than in surface spreading. Consequently, if suspended solids are not removed from the water prior to spreading, they must be removed by scraping or by filtering with subsequent cleaning of the filter by suction or by removal. The total amount and location of sediment and the size of particles are factors determining the frequency of cleaning.

Table 4 – *Average hydraulic head losses, infiltration rates, and hydraulic conductivities occurring in the aquifer material from 0–0.2 ft with no filter and with sand filter, third run*

Date	No filter			Sand filter		
	Head loss	Infiltration rate	Hydraulic conductivity	Head loss	Infiltration rate	Hydraulic conductivity
1956	ft	ft/day	ft/day	ft	ft/day	ft/day
Aug. 21	0.51	107	40.5	0.70	128	36.6
22	1.79	151	17.0	0.68	101	29.6
23	1.26	119	18.9	0.83	72	18.9
24	1.67	122	14.5	1.07	111	20.5
27	2.01	46	4.6	1.41	96	13.5
28	2.10[a]	44	4.2	1.44	93	12.9
29	...	39	...	1.76	103	11.7
30	...	33	...	1.81	89	9.8
31	...	30	...	1.90	81	8.5
Sep. 4	...	25	...	1.99	63	6.3
5	...	22	...	2.00	54	5.4
6	...	22	...	2.05	52	5.1
7	...	24	...	2.08	55	5.3
8	...	20	...	2.10[a]	46	4.4

[a] Total hydraulic head was 2.10 ft with the datum the 0.2-ft level in the aquifer material.

Table 5 – *Suspended solids in water within infiltrometers on various dates*[a]

First run		Second run		Third run	
Date	Suspended solids	Date	Suspended solids	Date	Suspended solids
1956	ppm	1956	ppm	1956	ppm
6/12	17	7/17	5	8/27	1
6/15	12	7/27	4	9/4	1
6/18	17	...	...	10/4	3
6/20	6	...	...	10/5	1,840
6/28	5	...	...	...	...

[a] Water sampled when changes in turbidity were visibly apparent.

Table 6 shows the amount of fines in the 0–0.01 ft depth of aquifer material after a six-day run without filters compared to the fines initially present in the aquifer. During this time, turbidity of the supply water was low. Total fines less than 0.1 mm in diameter increased appreciably in the 0–0.01 ft depth, and a deposit was visibly apparent on the surface of the aquifer after the run. The data indicate that most of the deposit was composed of particles less than 0.002 mm in diameter. Previous analysis of deposits from the water on the surface of the nearby pit showed 81 pct of the material to be less than 0.002 mm in diameter.

Although the water temperature varied during runs and between runs, a check of individual infiltrometers showed that the water temperature did not vary appreciably between infiltrometers. Maximum temperatures varied from 24° to 38°C, minimum temperatures from 24° to 32°C, and mean temperatures from 26° to 30°C for the three runs.

Conclusions—The total infiltration through the aquifer material was nearly doubled or more than doubled when the sand filter was used as compared to the aquifer material with no filter. The filters of ⅛- and ¼-inch pea gravels were not particularly beneficial. The sand filter delays the sealing that normally takes place due to sedimentation in the aquifer material with no filter. Sedimentation and sealing of pores occurred more rapidly in the aquifer material under the ⅛- and ¼-inch pea gravel filters than under the sand filter. A filter is desired

Table 6 – *Amount of fines from 0 to 0.01 foot of aquifer material inherently and after a six-day run*

Infiltrometer	Fines in aquifer material for 0 to 0.01 foot depth								Total infiltration for six-day run
	Inherent				After six-day run				
	0.1–0.05mm	0.05–0.002mm	0.002mm	Total <0.1mm	0.1–0.05mm	0.05–0.002mm	0.002mm	Total <0.1mm	
	pct	pct	pct	pct	pct	pct	pct	pct	ft
1	1.2	0.3	1.0	2.5	2.7	2.1	4.5	9.3	93
6	1.9	0.3	2.1	4.3	1.4	0.3	3.4	5.1	127
13	0.3	0.1	1.5	1.9	0.8	0.2	2.6	3.6	116
16	0.1	0.1	1.1	1.3	0.4	0.3	2.3	3.0	123

that removes particles through a depth and not on a thin plane, thus maintaining permeability equal to or greater than the underlying aquifer material.

Another factor in maintaining higher infiltration rates seems to be the effect of the interface between the filter material and aquifer material beneath. Particle sizes for the sand filter and aquifer material are quite similar whereas the ⅛- and ¼-inch pea gravel filters are appreciably larger than the aquifer material. Similarity in size appears to establish a stable interface which probably is conducive to maintaining more rapid flow.

A filter material is desirable that will (1) filter out suspended solids through a depth, (2) stabilize the interface, and (3) not reduce effective pore openings of the material beneath.

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Evapotranspiration Estimates from Heat-Budget Measurements over a Field Crop

V. E. SUOMI AND C. B. TANNER

Abstract—The heat-transfer processes which occur at the Earth's surface have direct bearing on many of the physical problems in agriculture that relate to the plant environment. The evapotranspiration from a crop can be estimated from the disposition of solar and sensible energy available at the earth-air interface. A suitable measurement of the heat budget, including net radiation, heat transfer by soil conduction, air-temperature gradient above the crop, and vapor pressure gradient above the crop, will account for the fraction of solar energy used hourly or daily for evapotranspiration. The simple theory, a brief description of the experimental equipment, and some illustrative measurements are discussed.

The importance of rainfall in agriculture is common knowledge. Equally important but not so obvious is the role of water loss. The moisture parameter of interest is really the difference of the two, that is, the soil moisture quantity, which can be measured directly by soil sampling. There are also indirect methods of obtaining soil moisture such as tensiometers and electrical conductivity block measurements. Aside from the disadvantage of the physical labor involved in obtaining the samples, the direct and indirect methods are likely to suffer from statistical error, unless a large number of measurements are taken. In addition it is difficult to transfer from values of tension or conductivity to volume of water per unit volume of the soil. (In this regard, the developments in soil-moisture measurement by means of neutron scattering are awaited with considerable interest. Here there appears to be a definite possibility of rapid sampling and good accuracy.) The purpose of this paper is to illustrate how the water loss at the Earth's surface can be estimated to good accuracy from the disposition of energy at the earth-air interface.

List of symbols—The following symbols are used.

R_n	net radiation
A	sensible heat flux (heating air)
S	soil heat flux
E	latent heat flux (evaporation)
β	Bowen ratio = A/E
L	latent heat of evaporation at plant temperature
ρ	air density
C_p	specific heat of moist air at constant pressure
T	air temperature, °C
∇_H	$\partial/\partial x + \partial/\partial y$
P	air pressure, *mb*
K_H	eddy coefficient of heat conductivity
K_w	eddy coefficient of vapor diffusivity
e	vapor pressure, *mb*
u	horizontal wind speed
ϵ	ratio of mole weights of water to air
R	specific gas constant
C	specific heat of the crop
ρ_c	density of the crop
Δ	finite increment

The heat budget—The heat budget of a volume the bottom face of which is the Earth's surface as shown in Figure 1 is, neglecting fractional heating

$$R_n + S + A + E + \int_0^z C_p \nabla_H (\rho ut)\, \delta z + \int_0^z \frac{L\epsilon}{R} \nabla_H \left(\frac{ue}{T}\right) \delta z + \int_0^z C\rho_c \frac{\partial T}{\partial t}\, \delta z + \int_0^z C_p\rho \frac{\partial T}{\partial t}\, \delta z + \int_0^z \frac{L\epsilon}{RT} \frac{\partial e}{\partial t}\, \delta z = 0 \qquad (1)$$

The first four terms represent the vertical heat (flux positive when flow is toward the volume) and the next two terms are the horizontal divergence of sensible and latent heat respectively. The last three terms represent the changes in sensible and latent heat stored in the volume. The change in the temperature of the crop and of the air are the sensible heat terms and the change of water vapor in the volume is the latent heat term. As $\delta z \rightarrow 0$, (1) reduces to

$$R_n + S + A + E = 0 \qquad (2)$$

This is the expression used by *Albrecht* [1943], *Sverdrup* [1936] and others. Since $\delta z > 0$ when vegetation covers the surface and measurements are made above the surface, it is necessary to evaluate the magnitude of the additional terms in (1).

Rider and *Robinson* [1951] have shown that the last two terms in (1) are only a small fraction of A and E during a clear day. They might be as

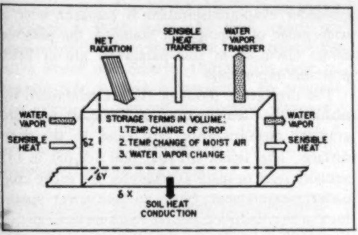

FIG. 1 - Schematic heat budget over a crop

large as ten per cent of A and E near sunrise and sunset or at night when $\partial T/\partial t$ is large and A and E at those hours are small. The heat stored in the crop is also negligible. Even when the crop is a heavy stand of corn, three meters high which yields 17 tons of silage to the acre, this heat is at most only one per cent of the total heat budget. Evidently during the day the storage terms can be ignored without introducing any appreciable error.

The divergence terms on the other hand may be large and to ignore them will introduce a large error. *Suomi* [1953] has shown, for example, that when measurements were made one to three meters above a crop of corn 2.5 m high, the divergence term can add as much as 40 pct to the evapotranspiration over that which would be obtained by (2). The divergence and storage terms can be minimized by taking the measurements near the surface so $\delta z \rightarrow 0$. We can test the validity of the assumptions used in the heat budget method by comparing its results against a more direct evapotranspiration measurement such as obtained with a lysimeter.

A properly exposed lysimeter will measure the total evapotranspiration as expressed in (1). The lysimeter used in this study has already been described *King, Tanner, Suomi* [1956]. A lysimeter, however, is not an absolute device. Its calibration depends on its area and its representativeness as well (sampling errors). While its tank area is easy enough to measure, the effective evapotranspiration area cannot be measured directly. Even though the lysimeter is not an absolute device, it still can be used for a test of heat budget evapotranspiration estimate. Ignoring for the moment the calibration of the instruments used for the heat budget measurement, if the ratio of the lysimeter evapotranspiration and the heat budget evapotranspiration is constant over a wide variety of weather conditions we will have demonstrated the reliability of the heat budget evaporation estimate. Stated differently this means that, provided the R_n and S terms are measured accurately, the partition of the residue into sensible heat flux and evapotranspiration is the same for both the heat budget and the lysimeter.

Calibration of the net radiometer and the soil heat flux instruments must be done independently. In this experiment, the net radiation is the largest term and is measured most accurately.

Instruments for heat-budget measurement—A schematic diagram of the instrument set up is shown in Figure 2. The divergence and storage terms in (1) are held to a low value by making the necessary measurements as near to the surface as possible. Measurements of net radiation R_n obtained with a net radiometer described by *Gier* and *Dunkle* [1951] or an improved model given by *Suomi* and others [1954] must be made one to three meters above the surface in order to keep the instrument's shadow from interfering with the measurement.

The soil heat conduction term S for the upper 10 cm of the soil is obtained from calorimetry *in situ*. Since the plant cover is highly variable, 12 thermometers, each of which measures the mean temperature change in a 10-cm column, are suitably placed to give the mean temperature change of the upper 10 cm of soil. The remaining soil heat flow below the 10-cm level is obtained with a heat meter [*Deacon*, 1950]. The heat meter, while very convenient, should not be used right at the soil surface because it interferes with moisture flow and subsequently the normal heat flow, and because a heat plate near the soil surface will be markedly influenced by the plant cover which may not be representative. The remaining sensible and latent heat transfer terms can be separated using the *Bowen* [1926] equation of the form

$$\beta = \frac{A}{E} = \frac{PC_pK_H\,\overline{(\partial T/\partial z)}}{L_eK_w\,\overline{(\partial e/\partial z)}} \tag{3}$$

Since the shape of the vertical moisture profile has approximately the same functional form as the vertical temperature gradient we can write $\left(\frac{\partial T/\partial z}{\partial e/\partial z}\right) \doteq \frac{\Delta T}{\Delta e}$. If we assume that $K_H = K_w$ the (3) reduces to

$$\beta = \left[\frac{C_pP}{L_e}\right]\left[\frac{\Delta T}{\Delta e}\right] \tag{4}$$

and we can obtain β by measuring the temperature and vapor pressure difference at two heights. There is considerable controversy regarding the equality of K_H and K_w. Some writers state that K_H/K_w is greater than unity during unstable stratification in the surface layer and less than unity with stable stratification. Others state that K_H/K_w should be set equal to the ratio of molecular diffusivities for air and water vapor or about 1.14. We see that β enters the expression for the solution of E in the form

$$-E = \frac{R_n + S}{1 + \beta} \qquad (5)$$

Thus the error in E will always be significantly less than the possible error in β due to an incorrect assumption concerning K_H and K_w. During conditions when A is much larger than E, the percentage error in E may be large but not as large as the error in β. However, in this case the absolute error in E will be small since E itself is small. If the ratio of heat-budget evapotranspiration to lysimeter evapotranspiration is constant over a wide range of atmospheric stability, the possible errors discussed in this paragraph are of little practical importance.

The divergence terms of (1) are minimized by making the temperature and vapor pressure gradient measurements very close to the crop surface. The terms $\overline{(\partial T/\partial z)}$ and $\overline{(\partial e/\partial z)}$ in (3) actually refer to space averages for the entire crop under measurement. Since no convenient space-integrating thermometers or hygrometers exist, a time-average gradient is usually assumed to represent a space-average gradient. When measurements are made at a point just above a heterogeneous plant cover, there is no *a priori* reason to assume that the time-averaged temperature and moisture gradients at that point represent the space-averaged gradients for a much larger area. The scale of the cover variability extends from a few mm (the size of a leaf) to several meters (the scale of the cover patchiness). Most of the unrepresentativeness is removed by swinging the

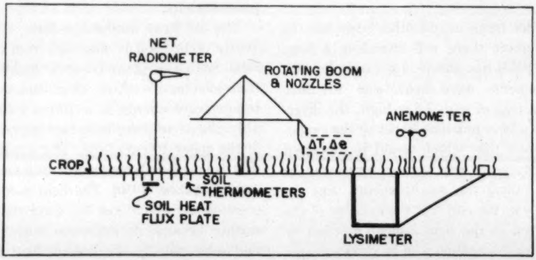

FIG. 2 – Schematic diagram of equipment used to obtain heat budget measurements

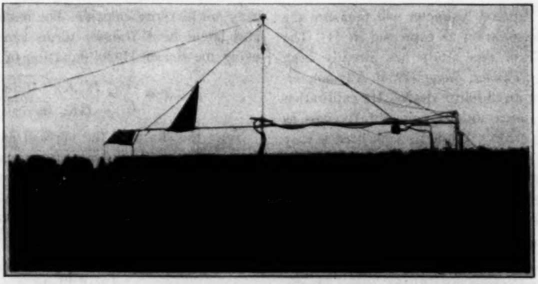

FIG. 3 – Space integrating boom

instruments in a 15-meter arc with the boom shown in Figure 3. Both space and time means are measured with this system. The boom travels the arc in about one minute. During this time an accurate time average is measured. An accurate time average is assured by obeying *Shannon's* [1949] sampling theorem which states that a variable whose highest frequency is *f* is completely specified if the sampling frequency is 2*f*.

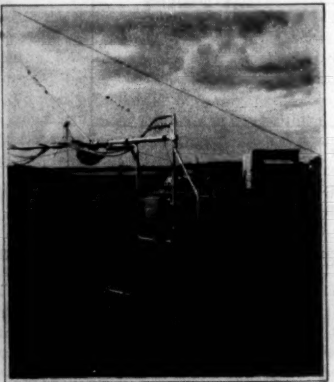

FIG. 4 – Air intake nozzles for measuring temperature and moisture gradients (aspirated thermometers are mounted on parallel bars for position reversal necessary to correct systematic errors)

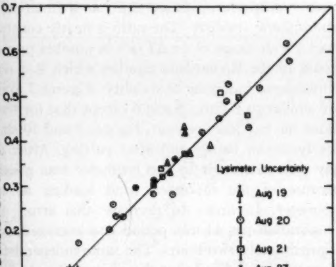

FIG. 5 – Evaporation per 44 minutes from heat budget and lysimeter measurements for August 19, 20, 21, 27, and September 3, 1955

Details of the thermometers and lithium chloride Dewcel hygrometers which meet these requirements have been published [*Tanner* and *Suomi*, 1956]. The temperature and dew point nozzles at the end of the boom are shown in Figure 4. To the authors' knowledge, this is the first time moisture and temperature gradients over a heterogeneous surface have been obtained in this manner. The temperature and moisture differences were obtained over a 60-cm height difference. The lowest position averaged only 10 cm above the mean crop height. On occasion plants even brushed against the bottom sensors, yet with

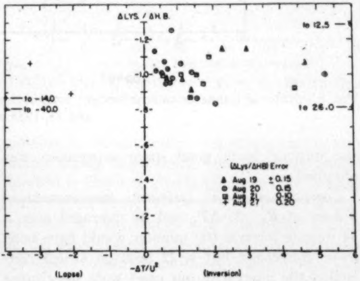

FIG. 6 – Ratio of lysimeter to heat budget evaporation as a function of atmospheric stability for August 19, 20, 21, 27, and September 3, 1955

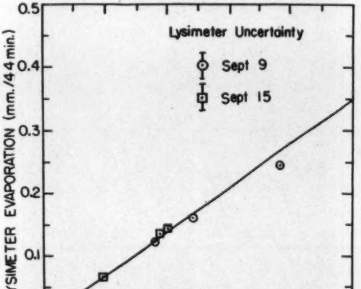

FIG. 7 – Evaporation per 44 minutes from heat budget and lysimeter measurements for September 9 and 15, 1955 after hay was cut

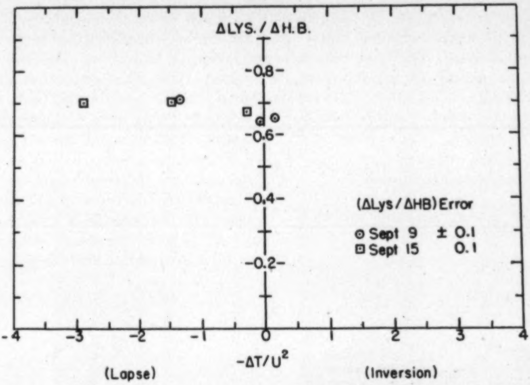

FIG. 8 – Ratio of lysimeter to heat budget evaporation as a function of atmospheric stability for September 9 and 15, 1955 after hay was cut

the moving boom good space integration was obtained.

Comparison with lysimeter measurements—Values of R_n, S, ΔT, and Δe averaged over a 44 minute interval (60 minutes would have been more convenient but a 22 position switch controlled the interval in our case) were substituted into (2) and (4) to yield the heat-budget evapotranspiration estimate. Figure 5 is a comparison of 44-min values of evapotranspiration from an alfalfa field at the University Experimental Farm at Hancock, Wisconsin, calculated from heat-budget measurements and obtained from lysimeter measurements for August 19, 20, 21, 27, and September 3, 1955. The bar in Figure 5 (lower right) indicates the range of uncertainty in the lysimeter measurement (wind loading on the lysimeter). Figure 6 shows the lysimeter to heat budget evapotranspiration ratio as a function of atmospheric stability. The ratio is nearly constant over a wide range of $(-\Delta T/u^2)$, a number proportional to the Richardson number which is a non-dimensional indicator of stability. Figures 7 and 8 are similar to Figures 5 and 6 except that for these dates the hay has been cut. Figures 9 and 10 show the lysimeter before and after cutting. After the hay was cut, error in the lysimeter was greater because of the increased wind loading of the lysimeter. In order to decrease this error, the evaporation per 44-min period was averaged over approximately two hours. The same independence of stability remained, but the ratio of the absolute values of the lysimeter to the heat budget changed materially. This indicates the sampling error of the lysimeter and shows further that it is not an absolute device.

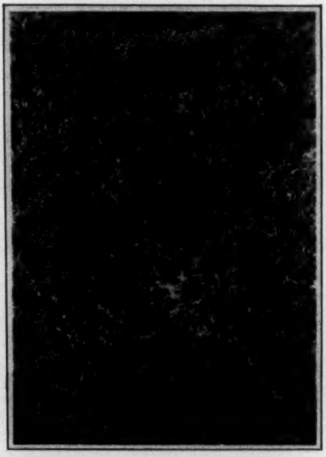

FIG. 9 – View of lysimeter with full cover; dotted line shows the position of lysimeter rim

Comparison with aerodynamic method—Some auxiliary wind data at one meter above the ground was also collected. The actual height above the crop is a function of crop height. It is possible to obtain an additional estimate of evapotranspiration from a product of the wind and the vapor pressure gradient in a manner similar to that used by *Pasquill* [1950],

$$E \propto u \, \Delta e \tag{6}$$

Figures 11 and 12 show a comparison between the heat budget evapotranspiration and $K u \, \Delta e$ where the normalizing constant K was computed to equate the daily evapotranspiration amounts obtained by each method. These figures show that there is little change in the constant over the three-day period and about ten per cent change over a week period due, presumably, to the change in crop height. After cutting, the normalizing constant changed again because of a change in crop height.

FIG. 10 – View of the lysimeter after the hay was cut

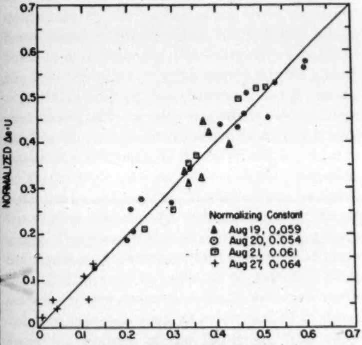

FIG. 11 – Plot of normalized $u \, \Delta e$ vs the heat budget before the hay was cut

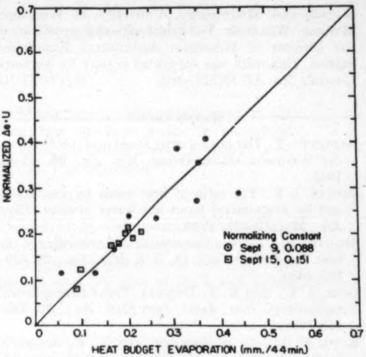

FIG. 12 – Plot of normalized $u \, \Delta e$ vs the heat budget after the hay was cut

This additional wind measurement makes it possible to obtain better evapotranspiration estimates during those times when the heat budget method is likely to give large errors due to small values of either R_n, or $(1 + \beta)$. Evidently a combination of heat budget and a simplified version of the aerodynamic method, enables one to make excellent evapotranspiration estimates over a wide range of atmospheric conditions.

Conclusions—The heat budget has been shown to yield very reliable estimates of evaporation from a field crop on an hourly basis over a wide range of wind speeds and atmospheric stability. By taking the trouble to arrange the experiment to obey Shannons sampling law and to use space integration, measurements can be made close to the crop surface without introducing any error due to the inhomogeneity of the crop surface. When this is done the divergence and storage terms can be neglected and the simple vertical heat budget which results is valid.

While the controversy over any possible difference in K_H, the coefficient of eddy heat transfer, from that of K_w, the coefficient for moisture transfer, is not clearly resolved under the conditions used in this experiment, no difference could be detected. In order to settle this controversy it appears necessary to increase the measurement and sampling accuracy an order of magnitude—no easy task.

Acknowledgment—Grateful appreciation is expressed to K. M. King, Soils Department, Ontario Agricultural College, for his effort during the data collection and reduction. This is a contribution from the Departments of Soils and Meteorology, University of Wisconsin, Madison, Wisconsin. Published with the permission of the Director of Wisconsin Agricultural Experiment Station. This work was supported in part by Air Force Contract No. AF 19(122)-461.

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Strength Studies of High-Density Snows

THEODORE R. BUTKOVICH

Abstract—Various strength properties of naturally compacted high-density snows, in the density range from 0.40 to 0.75 g/cm³ are reported. Test results are given for: unconfined compression; unconfined and confined double shear at various lateral pressures; ring, flexural, and centrifugal tensile strength, and torsional strength. The expression

$$\sigma = a(\gamma - \gamma_0)[1 + b(\gamma - \gamma_0)^2]$$

relating the various strengths σ to the density γ of snow fit all the measurements. The constants a and b are different for each strength test, while γ_0, the virtual intercept at zero strength, is constant for all tests. The results of various tests measuring the tensile strength of the snow compare favorably with each other. An attempt to apply some of the known failure rules was unsuccessful.

Introduction—Several experimenters have devoted some time to the study of the shear, tensile, and crushing strength properties of snow. The data they report however, are rather meager, and a comparison of values obtained by the various authors shows quite a difference in their results. It is suspected that this is due to the different types of snow tested, and conditions of temperature or techniques of measurement. Values found in existing publications are primarily for low-density snows, including new snow, old snow, and depth hoar (Schwimmschnee). The work reported in this paper is for naturally compacted snows of higher densities, from 0.40 to 0.75 g/cm³. The term 'high-density snows' as used in this paper means snow of the type that lies below the surface in the upper layers of the northern Greenland Ice Cap, in a no-melt zone. This snow has been naturally compacted by the weight of the overlying snow. Snow found in other regions of the Earth where there is no continuous accumulation is usually of the lower densities, varying from 0.1 to 0.4 g/cm³.

A 100-ft deep pit was excavated and a density and stratigraphy profile was made. From these profiles, layers were chosen which would give a wide variation of densities. In the 100-ft depth a total of 53 layers were selected, with a density variation from 0.40 to 0.65 g/cm³. The layers were sampled by drilling horizontally with a three-inch coring auger. The snow in the horizontal cores was quite homogeneous with respect to the density and grain size. The layers were selected so that no visible variations were included. A single three-inch vertical core hole was sunk an additional 55 ft down from the bottom of the 100-ft pit. The cores taken from this hole were also used in the tests to determine strengths for densities up to 0.75 g/cm³. These cores were less homogeneous because of stratigraphic variation or layering of the snow.

In conjunction with the excavation of the 100-ft deep pit, a snow laboratory was made by excavating an area of about 17 × 9 ft to a depth of eight feet. The excavation was roofed over, and snow platforms along its length were covered with wooden panels to provide table space.

The temperature in the pit below the 20-ft level was about −12°F which is the mean annual surface temperature in this region. All of the cores were left in the snow laboratory at least 12 hr before testing, in order to reach laboratory temperature.

The tests reported here were made on three-inch diameter cylindrical cores with few exceptions. Specimens of the lower density snows (below 0.45 g/cm³) were taken with a standard SIPRE snow tube, 2.28 inches in diameter.

Since the data reported in this paper were taken under field conditions, it was difficult to obtain any sort of temperature control. Laboratory temperature varied from day to day and even hour to hour, owing to the changing outside air temperature and to heat output from the test personnel and the lighting system employed.

It is known that temperature affects the crushing strength of ice, and also the shear, torsional, and tensile strength to a somewhat lesser extent. It was necessary to correct all the values to a common temperature for which 14°F (−10°C) was chosen. The correction used was 1.4 pct/°F for crushing strength, and 0.5 pct/°F for tension and torsional strength values. The correction factor used for tensile strength was used for the double shear tests also, assuming a similar temperature relationship.

These temperature correction factors were taken from temperature effect curves for snow-ice in SIPRE Research Paper 11 [*Butkovich*, 1954]. They are not necessarily accurate for snow, but were the best values available. In any case, the maximum correction, about 15 pct, is less than the scatter obtained for any set of tests before correction and certainly improve the values shown on the graphs.

Crushing strength—Three-inch diameter cylindrical cores were trimmed to lengths of 6.7 ± 0.4 inch (17.0 ± 1.0 cm) in a miter box and the ends finished as nearly plane parallel as possible. A Carver hydraulic press with either a 2000-lb or a 5000-lb Baldwin load cell mounted in its head was used to apply and measure the load. The load cells are rated by its manufacturer to be accurate to ±1 pct of the applied load. The loads were read on a Baldwin strain indicator, on which they were tracked to a maximum value. In many cases the load fell off to a lower value before actual rupture took place.

The snow specimens were broken at the ambient temperature of the laboratory. The rate of application of load was approximately constant, controlled manually and timed with a stop watch. The average rate was 7.4 lb/in^2 sec (0.5 kg/cm^2 sec) calculated by dividing the maximum load by the time required to attain it.

The specimens of snow often broke into characteristic shapes (Fig. 1). After the maximum load was reached and before the actual rupture took place, the specimens visibly deformed. The top and bottom mushroomed, and after rupture the broken specimens had two cones, one at each end, or two partially conical pieces.

The graph of the relationship of crushing strength to density (Fig. 2) shows that the crushing strength of high density snow is a linear function of density. Each point represents the mean value for at least six tests, and each circled point is a mean of a group of similar densities, taken from the same data. A few tests were performed on vertical cores from below the 100-ft level. These values are represented by x's on the graph and are for single tests.

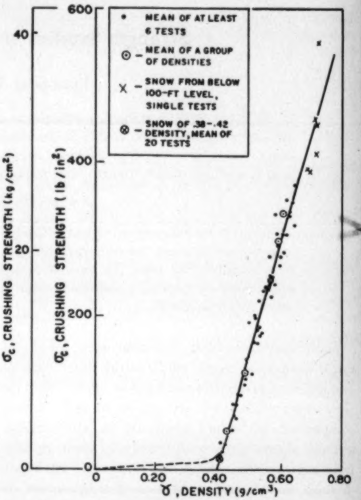

FIG. 2 – Relationship of crushing strength to density, snow from deep pit

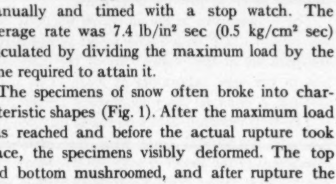

FIG. 1 – Typical compression breaks, snow from deep pit

An empirical relationship obtained from the data shown in Figure 2 for snow of density greater than 0.39 g/cm^3 is

$$\sigma_c = 1418(\gamma - 0.39) \tag{1}$$

where σ_c is the crushing strength in lb/in^2, and γ is the density in g/cm^3. This equation was determined by the method of least squares, has a virtual intercept at 0.39 g/cm^3 density, and holds to a maximum snow density of 0.75 g/cm^3. The broken line is the manner in which it is assumed that the strength values go to zero.

It was impossible to use the three-inch coring auger when the snow was of low cohesion (less than 0.40 g/cm^3 density), so the standard SIPRE snow tube was used. Tests were conducted successfully on snows between 0.38 and 0.42 g/cm^3 density. The values obtained, corrected to 14°F had a maximum temperature correction of 15 pct or 3 lb/in^2. The mean value of 20 tests is shown in Figure 2. For these low-cohesion snows, extreme care was exercised to prevent the samples from

TABLE 1 – *Compressive strength values for 4-cm cubes of snow; temperature 14°F [from Bird and Waterhouse, 1953]*

Mean density	Average unconfined compressive strength	
	Loaded normal to compaction plane	Loaded parallel to compaction plane
g/cm³	lb/in²	lb/in²
0.59	263	207
0.61	391	356
0.68	604	569

falling apart. Snow of lesser density fell apart as it was removed from the snow tube for testing.

A few tests on unconfined compressive strength of snow are reported in SIPRE Report 8 [*Bird* and *Waterhouse*, 1953], giving values obtained for 4-cm cubes. This snow of uniform grain size was disaggregated and artificially compacted. The values (Table 1) are considerly higher than those obtained for Greenland snow. The most likely explanation of this is the influence of the size of the specimens. SIPRE Research Paper 15 [*Butkovich*, 1955] shows the influence of sample size on strength of lake ice. Smaller cross sections give higher strengths, and the ratio of length to width also matters. End constraint increases with decreasing ratio of length to width, preventing the sample from failing under lower stresses.

Tensile strength—Various techniques are available for measuring the tensile strength of snow. One method developed for low density snows (below 0.45 g/cm³) uses a centrifugal tensile strength apparatus. This device consists of a cylindrical container into which snow from a standard SIPRE snow tube can be inserted. The snow specimen is notched slightly at the axis of rotation and driven by an electric motor controlled by a rheostat. RPM at rupture is read on a tachometer. The theory and a nomograph for this apparatus are given in *SIPRE* [1951a]. It was possible to test snows to a depth of 8.7 ft (265 cm) where the density reached 0.44 g/cm³. Testing snows of higher densities and consequently greater strengths would require a greater rpm than was available. The results of these tests are plotted in Figure 2. Each point represents a mean of eight tests. A number of tests using a centrifugal apparatus are reported by *Bucher* [1948]. Values for 23 specimens of density from 0.372 to 0.427 g/cm³ fall in the same range as those shown here with deviations of the same order. The mean density for these tests was 0.411 g/cm³, with a mean tensile strength of 9.2 lb/in². *SIPRE* [1951b] shows some similar tensile strengths obtained at the University of Minnesota, again for the lower density snows.

Another method for determining tensile strength was employed. A ring of the material is caused to fail by applying a compressive load normal to its axis. The test specimens were cut from three-inch diameter cores, to lengths of approximately 2½ in. A one-inch diameter hole was drilled coaxially. Tensile strength was calculated from the equation

$$\sigma_T = \sigma_\theta, = PK/\pi r_0 \qquad (2)$$

where σ_T is the tensile strength at failure, which is equal to σ_θ, the tangential stress at failure. P is the measured load at failure per unit of ring length, r_0 the outer radius of the ring, and K is the concentration factor, which, for these calculations, is dependent only on the ratio $\bar{r} = r_i/r_0$ where r_i is the inner radius of the ring. $K = -10.917$ was obtained from a table in *Ripperger* and *Davids* [1947]. The derivation of the above equation depends on the assumption that the tested material is truly elastic. Within the limitations of this assumption, a ring test will yield the tensile strength of a brittle material. Snow is primarily a viscoplastic material, with insignificant elastic deforma-

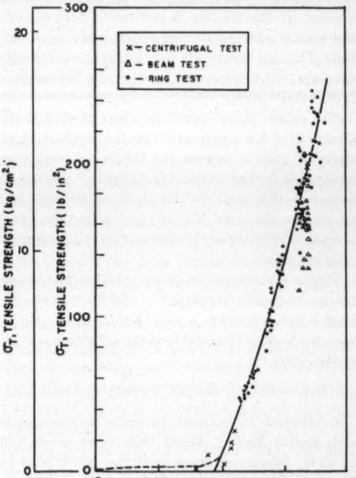

FIG. 3 – Relationship of ring tensile strength to density for high-density snow

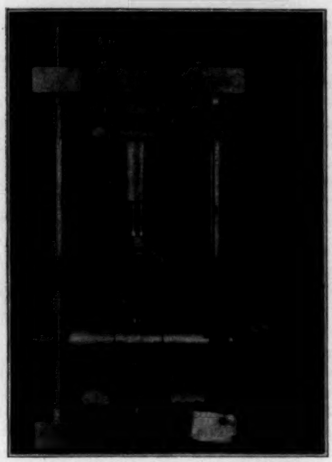

FIG. 4 – Double shear apparatus used for 1955 tests

tion at the lower densities. However, the elastic deformation increases appreciably with increasing density. If the loading is performed fast enough, the plastic effects decrease appreciably in magnitude. The ring specimens were loaded at a high rate (average of 9.5 lb/in² sec) at which the deformation is essentially elastic.

The failure plane for all cases was parallel to the direction of the application of the load. A finite stress at $r = r_i$ causes the failure. Actual tests have shown that, almost invariably, the failure begins at this point in the plane of the load and progresses along the line of the load to the outer boundary. The theory is discussed in the previously cited reference.

Figure 3 is the graph of the relationship of ring tensile strength (corrected to 14°F) to density. Each point represents a single value. An empirical equation was determined from the solid line portion of the curve

$$\sigma_T = 503(\gamma - 0.37)[1 + 2.88(\gamma - 0.37)^2] \qquad (3)$$

A number of flexural strength measurements with center loading beam tests were conducted by S. R. Stearns on snow from the 100-ft level in the deep pit. Values of 31 tests are plotted on Figure 3. The mean corrected to 14°F is 162 lb/in² at a mean density of 0.673 g/cm³. It is slightly lower than that obtained in ring tests.

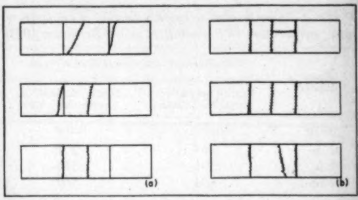

FIG. 5 – Sketch of typical breaks in double shear (solid lines denote apparatus, wavy lines denot breaks), (a) single shear with tension break as generally occurred for densities < 0.50 g/cm³, (b) double shear with tension break as generally occurred for densities < 0.50 g/cm³

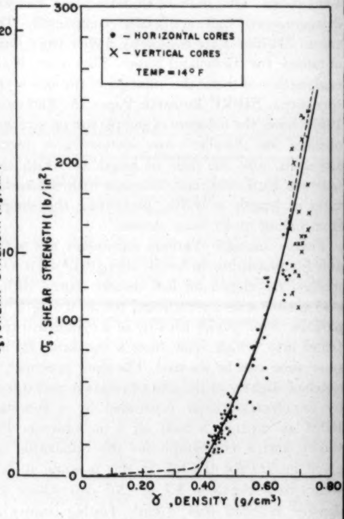

FIG. 6. – Relationship of double shear to density fo high-density snow

Shear strength—The apparatus used was modified Soil-Test, Inc., two-speed mechanica loading press. The shear box was 12-inches lon divided into three equal segments. The cente segment was attached to a mechanical loadin jack, through either a 500- or a 2000-lb provin ring. The two outer segments were attached rigidl to the base of the apparatus (Fig. 4). The tube wa equipped so that confined double shear tests coul also be made. A tapered pin retained a plug at one end of the tube, while a 200-kg Dillon dynamometer attached to a manually loaded piston was used to apply and measure a lateral load. With this device it was possible to obtain a maximum of 60 lb/in² lateral pressure on the three-inch diameter snow sample.

Several series of tests were made to obtain a relationship between density and shear strength for both the unconfined case and confined double shear at various lateral pressures. The specimens were taken horizontally from layers in the deep pit selected to give a wide range of densities. A number of vertical cores taken from below the 100-ft level were included. Loading was at a rate of approximately 5 lb/in² sec. At a very low load, the sample could be heard to fail, although the load did not drop off considerably. If the test was stopped at this point and the sample removed from the shear device for examination, it was always noted that the failure was somewhere near the center of the specimen. This failure was undoubtedly a tension failure similar to that which occurs in bending beams of brittle materials. Loading was continued after the tension failure, and the load increased until a new failure occurred where the load dropped off to zero.

Two types of failures were noted: (1) when the snow density was less than 0.50 g/cm³, the sample generally failed on only one shear plane (Fig. 5a); (2) when the density was greater than 0.50 g/cm³, the samples failed on both shear planes (Fig. 5b). However, all the data reported here were treated as though a double shear failure occurred in all cases. Figure 6 shows the relationship of the unconfined shear strength to density. The points represent values for single tests of horizontal cores, while the x's represent single values obtained from vertical cores. The relatively high amount of scatter is attributed to stratification of the snow, although higher strengths would be expected for the same mean density of horizontal (more homogeneous) cores. The upper broken line is a correction in this sense.

Table 2 – *Shear strength of disaggregated, artificially compacted snow from Fuchs* [*1949*]

Density	Shear strength	
g/cm³	kg/cm²	lb/in²
0.487	1.5	21.3
0.615	2.7	38.3
0.631	4.9	69.6
0.686	8.1	115.0
0.862 (snow ice)	12.2	173.2

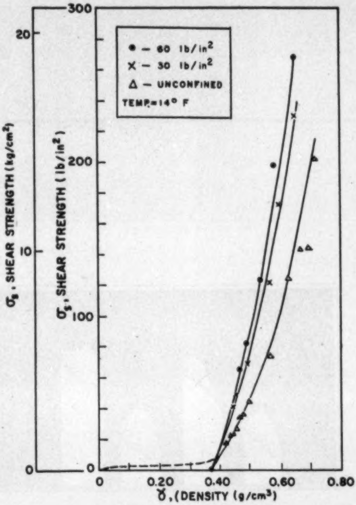

Fig. 7 – Relationship of shear strength to density for 0, 30, and 60 lb/in² lateral pressure

Several investigators have reported values for unconfined shear strength of snow. *SIPRE* [1951a] gives some values for lower density snows, and zero normal load. The mean is 7.1 lb/in² (0.5 kg/cm²) for 0.420 g/cm³ density. ***Fuchs*** [1949] reports a single shear value for disaggregated, artificially compacted snow as a function of temperature. Table 2 gives values taken from his curves at −10°C (14°F). These values are somewhat lower than those found for the Greenland snow, but there are several factors which may explain the difference. The shear specimens were all loaded at a much faster rate, in 1 to 2 sec. to failure. Another and probably more important factor was that the specimens were tested only seconds after they were compacted, not allowing age hardening.

Another series of tests was made using lateral pressures of 5, 15, 30, 45, and 60 lb/in². The sample length was 10.5 inches. The remaining portion of the 12-inch tube was occupied by the plug at one end to retain the test specimen, and the piston device with the Dillon dynamometer at the other. The desired lateral pressure was first ap-

FIG. 8 – Apparatus used for torsional strength tests

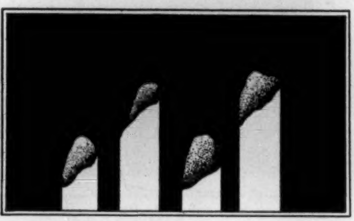

FIG. 9 – Typical torsion breaks, high-density snow from deep pit

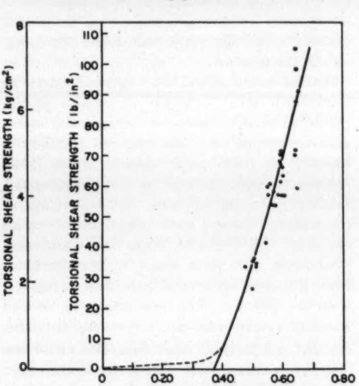

FIG. 10 – Relationship of shear strength to density for high-density snow

plied, and immediately afterwards the shearing force, keeping the lateral pressure constant.

After shear stress was applied, it was noted, for the specimens subjected to the low lateral pressure of 5 and 15 lb/in², that it was necessary to move the piston out to maintain a constant load, indicating that the snow specimen was expanding. For the higher lateral pressures of 45 and 60 lb/in², it was necessary to move the piston in to maintain a constant load, indicating a decrease in volume of the specimen. This was not due to simple consolidation of the snow because in several cases no decrease in volume occurred under 60 lb/in² lateral pressure during a relatively long period of time before application of the shear stress.

Figure 7 gives the relationship of temperature corrected shear strength to density curves for 0, 30, and 60 lb/in² lateral pressures. An empirical equation was obtained relating the shear strength to density for the three curves which is

$$\sigma_s = a(\gamma - 0.37)[1 + b(\gamma - 0.37)^2] \quad (4)$$

where σ_s is the shear strength in lb/in², and a and b the constants for the various lateral pressures. The values for a and b at 14°F are 333 and 7.04 respectively for zero lateral pressure; 558 and 5.44 for 30 lb/in² lateral pressure, and 643 and 6.13 for 60 lb/in² lateral pressure.

Torsional strength—A method for measuring shear stress by applying a torque to three inch diameter cores was tried on a few specimens. Only higher density snow was used because the handling necessarily would be damaging to the snows of lower density. Horizontal cores were taken for these tests from 0.50, 0.55, 0.60, and 0.65 g/cm³ density layers in the deep pit.

The apparatus (Fig. 8) consisted of a device which holds one end of the specimen stationary while the other end is free to rotate. A spring balance is attached to a lever arm on the rotating end for the determination of the torque. The apparatus was designed for square-end cross sections. It was necessary to put ends of the core into metal boxes, pack slush around them, and wait until it froze.

The rate of loading was approximately constant at 9 lb/in² sec. This relatively fast rate was used to reduce the plastic effects described in the tensile strength section of this paper.

The types of breaks were typical 45° helical torsion breaks that usually occur with brittle materials (Fig. 9). The stress distribution here is such that failure is in tension rather than in pure shear.

The torsional strength was calculated from an equation whose derivation can be found in *Timoshenko* and *MacCullogh* [1949, chap. 9]. The equation is

$$S = 16M_t/\pi d^3 \qquad (5)$$

where S is the unit shearing stress up to the elastic limit, M_t is the applied torque, and d is the diameter of the circular cross section. This equation is said to hold only within the elastic limit. In case of failure, the value obtained is called the torsional modulus of rupture.

Figure 10 is a plot of the relationship of the torsional modulus of rupture to density. The values are somewhat lower than those obtained in unconfined double shear or ring tension. High-density snow, which is a brittle material relatively weak in tension, when twisted, fails in tension on a plane inclined approximately 45° to the planes on which the shear stress occur.

Discussion of results—For all the strength data reported here, the density for which the extrapolated strength goes to zero lies between $\gamma_0 =$ 0.37 to 0.40 g/cm³. An attempt was made to express all the strength data in a common equation, involving only a difference in constants. It was found that the expression

$$\sigma = a\Delta\gamma(1 + b\Delta\gamma^2) \qquad (6)$$

could be made to fit all the curves, where $\Delta\gamma = \gamma - \gamma_0$ and γ_0 is the density at $\sigma = 0$. For the relationship of unconfined compression to density, being linear, the intercept was $\gamma_0 = 0.39$ g/cm³. For the relationship of ring tensile strength, torsional strength, and double shear to density for 0, 30, and 60 lb/in² lateral pressures, γ_0 was chosen as 0.37 g/cm³. A straight line was drawn through the intercept tangent to the curves; a in (6) is the slope of the stright line. The value of b which is an indication of the curvature, was determined by selecting a point on the curve at 0.67 of the maximum strength value and substituting the value of σ and $\Delta\gamma$ from here. The values of a and b that best represent the empirical data are shown in Table 3. The use of a virtual intercept is not meant to indicate that snow of lower densities have absolutely no strength, since strengths have been measured for these snows. *Kuroda* [1929] measured 63 g/cm² (0.9 lb/in²) shear strength for loose powder snows. A different type of structure exists below this critical density at the intercept. It has been observed that snow disaggregated and heaped always assumes an uncompacted density between 0.35 and 0.42 g/cm³. This is a characteristic of the substance snow and not of where snow came from. It is known that strength is some function of the contact area of the grains. At the lower densities, the number of contacts and the total contact area between grains decrease very rapidly. Studies are presently being conducted at the SIPRE Laboratory to determine this relationship.

TABLE 3 – *Values of constants*

Type of test	a	b
Unconfined compression	1418	0
Tension	503	2.88
Double shear, unconfined	333	7.04
Double shear, 30 lb/in² lateral pressure	558	5.44
Double shear, 60 lb/in² lateral pressure	643	6.13
Torsion	230	5.73

The evaluation of the ring test for the determination of the tensile strength of snow shows this test to yield results slightly greater than, but comparable with, those obtained by other means. The flexural strengths of simple beams obtained by Stearns agree very well with ring tension values, although the beam tests show slightly more scatter. The strength values obtained with the centrifugal tensile strength apparatus also fall in line (Fig. 2) although done on the lower density snow.

It can be expected that higher values of tensile strength would be obtained with ring tests than

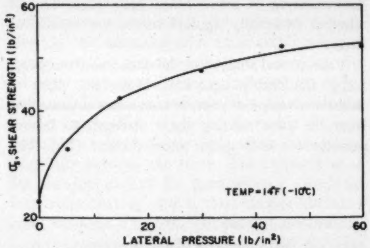

FIG. 11 – Relationship of shear strength to lateral pressure for snows of mean density of 0.45 g/cm³; each point represents a mean of ten tests

with beam or direct tension tests because of the extremely small volumes with critical stress involved in the rings. Among others, *Jellinek* [1957] shows that an increase in tensile strength occurs as the volume of the test specimens decreases. His analysis is based on a definable distribution of imperfections in ice. This distribution is considered in relation to the strengths of the imperfections. Each imperfection can withstand stresses up to a certain critical value. When the critical stress is exceeded, the imperfection opens up to a crack and the specimen ruptures. Since the probability for the weakest imperfections to occur in small volumes is less than for larger volumes, smaller volumes will give higher values of strength. The maximum tensile stress in the critical section occurs at the inner boundary $r = r_i$. A slight plastic deformation occurs directly under the load which causes such a redistribution of load that the stress is distributed over a finite area. If the material is strong in compression, such a redistribution would not materially affect the stress at an appreciable distance from the load.

The tests for the determination of the shear strength of snow were performed in direct shear. The results by themselves are quite reproducible. The unconfined shear tests give results of approximately the same magnitude as the ring tension values, with the latter being somewhat higher, probably because of the volume effect discussed in the previous paragraph. High-density snow is a granular substance, with more or less rounded particles. The total contact area of the bonds between the particles is related to the density. Both shear and tension failures are primarily intergranular rather than intragranular, with bonds being broken rather than the grains. For an open network such as exists for snow, it is quite obvious that shearing of bonds takes place regardless of whether externally applied forces are tensile or shear.

A theoretical analysis of the data was attempted, using Coulomb's equation. However, when a Mohr's envelope of rupture curve was constructed from the data relating shear strength to lateral pressure for 0.45 g/cm^3 snow density (Fig. 11), the envelope of rupture has a pronounced curvature instead of being a straight line. Two other known theories of failure, that is Tresca's maximum shear stress rule and Nadai's octahedral shear stress rule were considered for the analysis, but were rejected because they were not found to be useful.

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Studies on Wave Propagation in Granular Media

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Abstract—Experimental studies relating to the propagation and attenuation of disturbances in unconsolidated materials encouraged a theoretical investigation suggesting a mechanism governing propagation in such materials. From these physical considerations it is inferred that a disturbance imparted to a granular material is propagated in two principal parts. One consists of a wave of small amplitude which anticipates a wave of much higher amplitude propagating at a lower velocity. The first wave is called here a precursor and is identified with the visco-elastic deformation of the grains of the unconsolidated material. The second component propagating at a lower velocity and carrying most of the energy imparted by the disturbance is identified with consolidation, accomplished by filling the voids between the grains. It is thus inferred that there would be appreciable dissipation of energy associated with the second wave and little attenuation of the precursor wave. Further experiments were conducted to check these conclusions. The results of these experiments show the composite wave structure predicted from theoretical considerations.

Introduction—In attempting to extend mathematical studies on wave attenuation in visco-elastic materials, *Mattice* and *Lieber* [1953], to the depiction of the propagation of large disturbances through granular media the need for understanding the mechanism of propagation in such materials became evident. Some basic theoretical and experimental work has been carried out relating to the propagation of elastic waves in granular media by *Takahaski* and *Sato* [1949], *Gassmann* [1951], *Mindlin* and others [1951], and *Duffy* and *Mindlin* [1956]. In these studies the granular materials are represented by models consisting of rigid and consolidated elastic spheres. These investigations model a terminal phase of a more general transmission process and mechanism which is considered in this paper. It was therefore helpful to devise new experiments more representative of actual conditions to guide our thinking on this problem.

From physical considerations it appeared that the attenuation of a pulse in granular material is accounted for in large measure by the dissipation accompanying consolidation. From this it was inferred that the packing caused by the pulse decreases in the same direction the wave attenuates. Also possible, is the visco-elastic transmission of a pulse when repeated pulses of equal magnitude no longer increase the packing of the sand. Accordingly, if the pulse is increased in magnitude; the sand may continue to consolidate until it becomes virtually consolidated with respect to this magnitude. At such a time the pulse will again be transmitted visco-elastically.

Preliminary experiments were designed to check this reasoning and provide a basis for gaining physical insight to the mechanism governing propagation. The results of these experiments served as a guide in formulating a physical theory for a mechanism governing the propagation of a finite disturbance in granular materials. In these experiments the energy dissipated by dynamic consolidation and by intergranular friction was accurately measured.

The physical theory leading to this mechanism is based upon Hertz's generalization of Gauss' principle of least constraint. In this extension of Gauss' principle it is shown that it remains valid for impulsive loading and when the conditions of constraint depend explicitly upon time. The theory treats a granular material such as sand as a system of discrete particles which retain their identity in all encounters and are capable of moving relative to each other. The cases of perfectly smooth and rough particles are discussed separately. In addition to explaining qualitatively the results of the preliminary experiments, the physical theory predicts the existence of a small-amplitude precursor wave anticipating the wave carrying the principal part of the energy imparted by a disturbance. The precursor wave is identified with the elastic deformation of the grains and it is propagated with the velocity of a wave transmitted elastically between the grains. The propagation of the principal part of the disturbance is associated with consolidation and is thus propagated at a lower velocity. The principal part of the disturbance is therefore strongly attenuated by the large friction forces accompanying consolidation.

Experiments were then designed and conducted to detect the composite wave structure and in particular the precursor wave predicted by the propagation mechanism.

PRELIMINARY EXPERIMENTS

Consolidation produced by transient loads—A transparent plastic tube one and one-half inches in diameter and eighteen inches long was fitted with a brass cap at one end (Fig. 1). A steel piston was machined to fit the inside diameter of the tube.

The one end was capped and the tube filled with sand. To facilitate observation colored sand layers were introduced at intervals of one and one-half inches between uncolored layers. The initial locations of the colored layers were marked in the tube.

The piston was placed in the open end of the tube in contact with the sand and then struck repeatedly by a hammer and the new locations of the colored layers observed.

Visual evidence of progressive consolidation—It was found that after the first impact the packing near the piston, or source, was appreciably increased. This increase of packing diminished rapidly away from the source until only the original packing was evident. Following the second impact the packing near the source increased further, but only slightly, and the zone of maximum packing moved away from the source. Beyond that region the packing attenuated as before. Subsequent impacts had the same effect as the second impact, extending the packing into the sand.

When, following several impacts, the packing extended into three-fourths of the tube, the layers of sand in the remainder of the tube moved toward the piston. This may be explained by the packing near the piston becoming so large that the friction force between the sand and the tube resulting from a blow caused the plastic tube to move before the last one-fourth of the sand. Thus the relative movement of the colored layers would be toward the piston. However, this effect is a characteristic of the tube and is extraneous to the purpose of the experiment.

Energy dissipation in sand—The same plastic tube was supported as a pendulum, using a V-arrangement of two wires at each end to prevent lateral motion. A ten pound steel weight was also suspended by a similar V-support so that at the bottom of its arc it would strike the piston. Potential energy was introduced by deflecting the hammer along its arc to a pre-assigned height and arresting it there with an electromagnet.

A sheet of aluminum was placed parallel to the plane of the arcs subtended by the two pendulums.

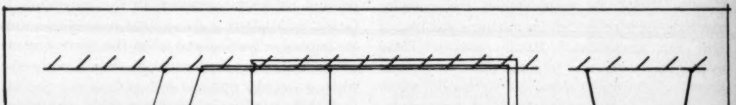

FIG. 1 – Apparatus used to measure energy dissipation in sand

It was covered with tracing paper on the side facing the pendulums. Pointers were attached to the tube and weight, extending approximately $\frac{3}{16}$ inch from the aluminum sheet. A magneto connected to the pointer and the sheet caused sparks to burn holes in the tracing paper. This provided an accurate trace of the motion of both pendulums, without impairing their motion.

The hammer was released by the electromagnet and the spark-producing magneto started. The pendulum then struck the piston. As the collision does not lead to a complete transfer of energy, the hammer would follow through. The tube of sand was allowed to attain its maximum height and was then arrested upon its return to prevent a further collision.

Impacts corresponding to the same initial height of the hammer were repeatedly applied. Following each impact, the tracing paper was moved and a reference line scribed using a level.

By subtracting the energy remaining in the hammer after collision from its initial energy, the energy transferred to the piston in the sand tube was determined. Using the weight of the sand tube and its initial and maximum elevation, the mechanical energy remaining in the tube and its contents were determined. The difference between the initial and terminal values of the mechanical energy in the tube is the energy absorbed by the sand.

In order to observe the reversible deformation of the sand as distinguished from the irreversible deformation (dissipative) the initial and terminal position of the piston relative to the tube were recorded. Using the apparatus just described, a pencil was attached to the plastic tube and a piece of paper taped to the shank of the piston. The pencil trace on the paper measured the motion of the piston, relative to the tube, produced by striking the piston with the hammer. This measurement was determined by the reversible and irreversible deformations. Following the impact, there is a partial recovery of the piston toward its initial position. This recovery is associated with the elastic deformation. The difference between the initial and terminal positions of the piston is therefore a measure of inelastic deformation.

Measurement of energy dissipation—It was found that when sand was poured in the tube without further packing it absorbed approximately 60 pct of the energy imparted by the first impact and dropped off sharply on the next two impacts (Fig. 2) thereafter remaining constant at about 43 pct for impacts of equal intensity. If the energy imparted was doubled, the energy absorbed increased to approximately 50 pct and then decreased as before to approximately 43 pct for the second impact and subsequent impacts of equal intensity.

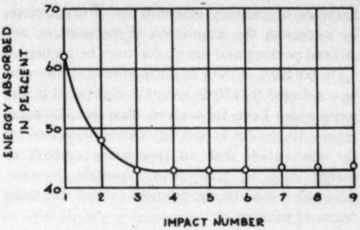

FIG. 2 – Per cent of impact energy absorbed on successive blows by sand confined in a tube

When the dissipation attained the asymptotic value of 43 pct subsequent packing was not visible. The energy imparted by the hammer was larger than the energy transferred in the visual experiment on the progression of packing. Thus, following two or three impacts, the sand became so packed that the tube was accelerated by friction between the sand and the tube wall. It is probable that the energy dissipation occurring for subsequent blows was caused by friction against the wall of the tube accompanying the seemingly elastic deformation of the sand, by internal friction, and by motion of the sand near the capped end of the tube. The latter was verified by removing the cap leaving a free sand surface. It was found that the sand did not lurch forward as if suddenly energized by a wave passed through it. This suggests that most of the energy is transferred to the tube by friction rather than by a normal force on the cap.

Comparison of reversible and irreversible deformations—The initial impulse caused a permanent movement of the piston that was approximately four times the reversible deformation. The second impulse produced a permanent deformation that was approximately twice the reversible deformation. The permanent deformation produced following the third impulse was somewhat smaller than the reversible deformation. All the subsequent impacts produced reversible deformations. The permanent displacement can therefore be attributed primarily to consolidation.

This experiment considered in conjunction with the previous one shows that the energy dissipated decreases significantly with increased consolidation of the sand. Thus, considerable dissipation is found to accompany consolidation. Furthermore, by increasing the magnitude of the impulse, additional packing and dissipation may be produced.

On the basis of the visual experiment it may also be concluded that little energy is dissipated in the zones which have for a given blow become saturated with respect to packing. This is supported by the observation that an appreciable amount of energy must be transmitted through the consolidated region to significantly extend the same degree of packing.

A mechanism governing the propagation of a disturbance in granular media—The correlations found in the experiments described between propagation and consolidation were helpful in suggesting a mechanism that may govern the propagation of a disturbance in granular materials. According to this mechanism, a disturbance propagates in such materials in two principal parts. The first part consists of a weak precursor wave associated with essentially elastic deformations of the grains transferring momentum normal to their contact surfaces, and thus propagating at the speed of sound in the grains. The second part, propagating at a lower velocity transmits most of the energy imparted by the disturbance, is identified with the interpenetration of the grains, and thus with consolidation.

The existence of a precursor wave and its relatively small amplitude was inferred by assuming that Gauss' principle of least constraint can be extended to collision phenomena. Such an extension to impulses was later found to have been carried out by *Hertz* [1896, pp. 76 and 253]. In adapting Gauss' principle to a collision model depicting grain interaction, it is here postulated that the grains retain their individuality in the course of time (during interaction) and that this is expressible by conditions of constraint which determine the admissible displacements of the individual grains. The conditions of constraint identified with the individuality of the particles may be expressed in geometrical terms by asserting that the grains cannot coincide. Displacements compatible with these conditions of constraint are then the virtual displacements of the system. Only displacements which do not bring the particles into coincidence are therefore admissible.

If the grains are perfectly smooth, then momentum is transferred only in directions perpendicular to the surfaces of contact and the forces generated by the conditions of constraint cited above are perpendicular to these surfaces.

According to Gauss' principle of least constraint the real motion of such a system is determined by the condition that the total constraint generated in this manner during collision be a minimum. This requires that the total change of momentum normal to the contact surfaces be less for the real motion than for any other motion consistent with the constraints and the initial conditions. In the presence of voids, the particles minimize constraints by interpenetration.

The energy transmitted normal to the contact surfaces which according to Gauss' principle is a minimum for the actual motion is propagated elastically between the grains at the speed of sound in the grains, and is identified here with a precursor wave. Strictly speaking, the propagation between the grains is elastic only if they are regarded as perfectly elastic bodies and if friction between the grains is neglected. The energy transported by grain interpenetration is propagated at a lower velocity and according to Gauss' principle should propagate most of the energy imparted by a disturbance. It is also inferred that when the voids are not sufficiently large to admit grain displacement leading to consolidation, all of the energy imparted by a disturbance would propagate elastically and a distinct precursor wave is not to be expected.

Anthropomorphically speaking, the above considerations may be expressed by the statement: The particles move where they encounter minimum resistance and thus naturally penetrate the voids rather than generate large collision forces whenever and wherever such alternatives present themselves.

In order to establish the physical reasoning leading to the mechanism outlined above on an accepted physical foundation, it is necessary that Gauss' principle be valid when the constraints depend explicitly upon time; as is the case when conditions expressing the impenetrability of the grains are formulated in a Galilean frame of reference. Hertz has demonstrated with complete generality that Gauss' principle holds when the equations of condition (constraint) contain time explicitly.

The next problem is to extend the application of Gauss' principle to such cases where the grains are not perfectly smooth. As friction forces resisting consolidation are then generated it is necessary to consider their effect upon the composite wave structure inferred in the case of perfectly smooth grains. The friction force also affects the precursor in a manner which probably can be well represented by a visco-elastic material.

Hertz [1896, pp. 76 and 253] postulated that the particles of a mechanical system are in general rigidly connected by differential equations of condition and that the motion of the system as a whole is governed by a law that is formulated without introducing the concept of force. In this manner Hertz deduced the Newtonian laws of motion and the principles of analytical mechanics and demonstrated that the forces impressed within and upon a system are determined by rigid connections existing between its particles and those of other systems. In demonstrating this Hertz introduced the concept of concealed masses whose connection with the observable particles is made apparent by the forces which they impart by their motion, to the observable particles.

Although by postulating the existence of concealed particles and rigid connections Hertz was able to deduce the Newtonian laws and the principles of mechanics from his fundamental law, he recognized the need to justify these rigid connections on strictly physical grounds. If it is postulated that interacting particles have an individuality which is maintained in the course of time then conditions which exclude displacements that would bring particles into coincidence may be regarded as rigid conditions applying to all particles of a system. According to this idea, the rigidity of the constraints is identified with and determined by the individuality of the particles. This may provide a physical concept upon which the notion of rigid connections, which are indispensable to Hertz's brilliant work, may be founded. If all the strictly rigid connections of a mechanical system are thus attributed to the individuality of its observable and concealed particles then it follows from Hertz's mechanics that all forces generated within the system are determined by this property of matter, that is, by its impenetrability.

In a granular material the observed particles are the individual grains, whereas the particles that account dynamically for the friction forces between the grains are in the sense of Hertz, the concealed particles of the system. Accordingly, the interaction of the concealed masses with each other and with the observable particles (the grains) are assumed here to be subject to the rigid connections through which their individuality is asserted. (Hertz postulated that in general the rigid connections may be expressed by linear homogenous differential equations relating the first differentials of the moduli of the vectors denoting the positions of the particles. Only in the particular case of Holomonoic systems are these equations integrable and are thus equivalent to finite equations of condition.)

It is now convenient to formulate Gauss' principle of least constraint analytically so that it may be referred to in describing a mechanism for propagating a disturbance in granular materials consisting of rough grains.

Consider a mechanical system consisting of particles with masses $m_1, m_2, \cdots m_m$, subjected to the impelling forces $F_1, F_2, \cdots F_m$, respectively. Let these particles be connected by rigid conditions of constraint which determine the admissible displacements that may be produced by these forces. In order to introduce a measure of constraint in terms of which Gauss' principle may be stated, it is sufficient to consider a representative particle of the system. Let $\overline{OA_1}$ be the displacement of particle i that would be produced by the impelling force F_i in time dt if the particle were free. Because of the constraints, the actual displacement in this time interval will be $\overline{OB_i} \neq \overline{OA_i}$. The constraint thus produces a change in the motion represented by the vector difference $\overline{OC_i} = \overline{OA_i} - \overline{OB_i}$. Gauss' principle states that the actual displacement of a system in time dt is determined by the condition that the sum $C = Mi\ \overline{(OC_i)}^2$ be a minimum. Thus the principle asserts that C, which measures the total constraint of the system, shall be less for the actual motion than for any other motion compatible with the constraints.

It is noted that the contribution of particle i to the total constraint of the system is weighted by its mass m_i. Accordingly, the minimization of C implies that the system moves so that changes of displacement produced by the constraints of the smaller masses are increased if by so doing the changes of displacement produced by the constraints of the larger masses are decreased.

Consider a mechanical system consisting of particles identified with both the individual grains of a granular material and with the concealed masses whose motion accounts for the friction forces acting tangent to the grain surfaces, when they move relative to each other. The masses of the grains which in this model are assumed to retain their individuality in the course of time are clearly much larger than the concealed masses accounting for the friction forces resisting consolidation. The finite volume of the grains should in general also be taken into account, in the consideration of the constraints generated as a consequence of the grain individuality. Accordingly the constraints connected with the displacement of the grains, in rotation as well as in translation should be considered, where the former are weighted in the expression for the total constraint by the moments of inertia of the grains.

A mechanism for propagating a pulse in a granular material consisting of rough grains may be described in terms of this composite mechanical system by considering qualitatively the constraints which account for the forces applied normal and tangent to the contact surfaces.

The grains interact by transferring momentum normal and parallel to the contact surfaces. From the above considerations, these forces have their origin in the constraints associated with the grain masses and with the concealed masses respectively. If we now assume that the grains and the concealed masses constitute a composite mechanical system governed by Gauss' principle, it follows that the change in displacement admitted by the forces originating from the constraints associated with the grains are much smaller than those admitted by the concealed masses.

If a disturbance is applied to some grains imbedded in a granular material they are accelerated, and if not initially in contact, move until they engage neighboring grains to which they impart forces normal and tangent to the contact surfaces. The constraining forces generated normal to the contact surfaces may be resolved into forces acting through the centers of mass and couples. The constraints are then respectively proportional to the masses and the moments of inertia of the grains. In the first case the grains assert their individuality by resisting displacement of their centers of mass and in the second case by resisting displacements in rotation.

It follows that changes in displacement admitted by constraints generating the normal stresses should be much smaller than those admitted by the constraints identified with the tangential stresses. As this result appears to be general within the framework of the physical theory in which it is obtained, it may be used qualitatively to infer a mechanism for transmitting a pulse in granular materials. Since the mode of transmission of a pulse in such materials is determined by the motion of its grains compatible with all of the constraints of the system, it follows that in the presence of voids the transmission of energy accompanying displacements tangent to the contact surfaces, would be much larger than the energy transmitted normal to these surfaces. This implies as in the case of perfectly smooth grains that a pulse would be transmitted in essentially two distinct parts. The first part, identified with the normal stresses, would therefore have a small amplitude and propagate with the speed of sound in the grains. The speed of sound is a function of the initial normal contact stress as reported by *Duffy* and *Mindlin* [1956] according to their experimental results. The propagation of the second part is identified with consolidation and would therefore, transmit most of the energy at a velocity which is appreciably lower than the speed of sound and would be strongly attenuated by the friction forces acting tangent to the contact surfaces.

Note that the mode of transmission of a pulse in granular materials proposed here has been inferred without using the conservation laws for momentum and energy. This is possible since the transmission of energy and momentum in the system considered, is completely determined by the preferred paths of the particles which have been here directly inferred from Hertz's extension of Gauss' principle of least constraint. Accordingly, the concept of force and energy are not used in the statement of Hertz's fundamental law but rather appear as consequences of this law.

When voids sufficiently large to accomodate the grains are not available the composite wave structures consisting of a weak precursor propagating acoustically, followed by a strong and rapidly attenuating pulse identified with consolidation, should coalesce into a single pulse propagating at the speed of sound. This pulse may also be attenuated although to a lesser degree by intergranular friction.

Some energy may also propagate elastically through couples resulting from the normal stresses applied to grains of finite size. This may produce another elastic wave propagating at a lower velocity than the precursor. It is believed, however, that this wave would probably be of much smaller amplitude than the precursor and be masked by the large disturbance identified with consolidation. If the mechanism proposed here is essentially valid, elastic waves of the same type as the precursor would be repeatedly generated and radiated as weak secondary waves from the principal part of the pulse identified here with consolidation.

The experiments described in the following section of the report were designed to evaluate the propagation mechanism proposed here. In so doing, the precursor wave predicted by the mechanism was detected in all cases where it was anticipated.

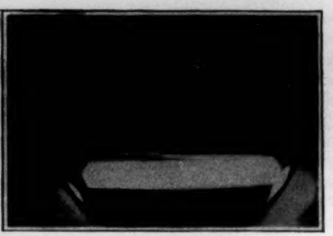

FIG. 3 – A disturbance propagated through two inches of dry sand, as recorded by a strain-gage pickup; 1000 cycles per second sweep; (1) precursor wave; (2) sharp rise of principal disturbance (note that the maximum amplitude of large disturbances is off screen); (3) coda of wave (see Fig. 5); (4) sweep of oscillograph before and after the disturbance

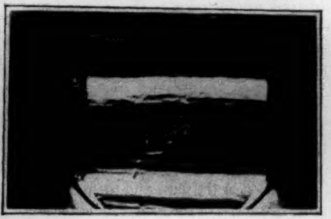

FIG. 4 – A disturbance propagated through five inches of sand, as recorded by a strain-gage pickup; 1000 cycles per second sweep; (1) precursor wave; (2) sharp rise of principal disturbance (the maximum amplitude is off screen); (3) coda of wave (see Fig. 5); (4) sweep of oscillograph before and after the disturbance; (5) displacement of neutral position of the beam; this occurred after the mechanical disturbance

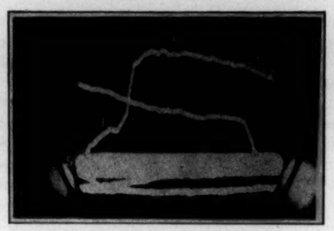

FIG. 5. – A disturbance propagated through 30 inches of sand, as recorded by a strain-gage pickup; 60 cycles per second sweep; (1) precursor wave; (2) sharp rise of principal disturbance; (3) maximum amplitude of principal disturbance; (4) coda of principal disturbance (the recurrent sweep of the oscillograph causes the line terminated at the right to be continued at the left of the screen; thus the image of the latter portion of the wave is superimposed upon the image of the first portion of the wave); (5) sweep of the oscillograph before and after wave

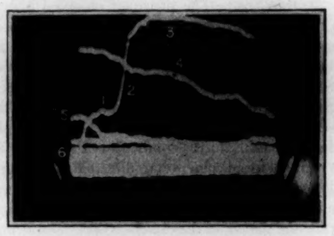

FIG. 6 – A disturbance propagated through 30 inches of sand, as recorded by a strain-gage pickup; 60 cycles per second; (1) precursor wave; (2) sharp rise of principal disturbance; (3) maximum amplitude of principal disturbance; (4), (5) coda of principal disturbance (the recurrent sweep of the oscillograph causes the line terminated at the right to be continued at the left of the screen; thus the image of the latter portion of the wave is superimposed upon the image of the first portion of the wave); (6) sweep of the oscillograph before and after disturbance

EXPERIMENTS RELATING TO THE PRECURSOR WAVE

Instrumentation—A pickup was constructed to record time changes of displacement of a granular material subjected to impulsive loads. The pickup consisted of a strain gage glued to a 0.008-inch thick steel diaphragm resting on a shoulder machined $\frac{3}{8}$ inch from the open end of a $1\frac{1}{2}$-inch long circular cylinder closed at one end. A circular insert was used to retain the diaphragm on the shoulder. The strain gage was in one arm of a wheatstone bridge. The unbalanced voltage produced by deflections of the diaphragm was amplified and fed to a cathode-ray oscilloscope. The screen was photographed with a Dumont cathode-ray oscilloscope record camera. The pickup exhibited the characteristics desired, being only sensitive to deflections of the diaphragm.

The pickup was imbedded in dry sand and so oriented that the diaphragm was normal to the direction of propagation produced by a disturbance at the surface of the sand. The depths of the sand layers used in these experiments were approximately 2, 5, and 30 inches. The packing varied with repeated blows on the piston. The shutter of

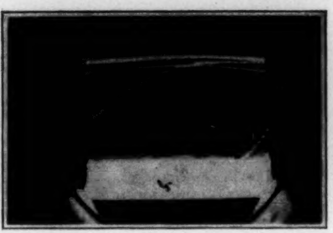

FIG. 7 – A disturbance produced under conditions similar to those in the sand tests, propagated through two inches of modeling clay; 1000 cycles per second sweep; (1) rise of disturbance; (2) rise of disturbance, continued because of oscillograph's recurrent sweep; (3) maximum amplitude of disturbance; (4) coda wave; (5) sweep of oscillograph before and after disturbance; the absence of a precursor is noted

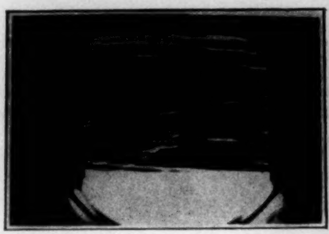

FIG. 8 – A disturbance propagated through two inches of modeling clay, as recorded by a strain gage pickup; gain of oscillograph increased to accentuate region (1) of the previous photograph, 1000 cycles per second sweep; (1) rise of disturbance; the absence of a precursor wave is noted

the Dumont camera was opened before and closed after the impulse.

Measurements—The precursor observed here is a small amplitude, sharp wave that preceded another disturbance having a much larger amplitude. In all photographs the horizontal axis measures time and the vertical axis the displacement of the diaphragm, which is proportional to the force imparted to it by the sand. The photographs thus give a time history of the force transmitted to a plane perpendicular to the direction of propagation of the wave. The heavy horizontal line is produced by numerous sweeps made by oscillograph while the shutter of the camera is open. The strain-gage pickup using an alternating current amplifier with large capacitance is capable of sustaining a steady signal for a sufficient period of time to record the wave shape. A two-inch specimen of loosely packed sand requires a sweep of about 1000 cycles per second to separate the precursor from the principal disturbance. When the sensitivity was increased to accentuate the precursor wave the maximum amplitude of the strong wave was off the oscillograph screen as shown in Figures 3 and 4. With a five-inch sand specimen the time interval separating the arrivals of the two disturbances is increased.

As the depth of sand was increased to 30 inches it was found that the time interval separating the arrival of the two waves increased further. This definitely established that the two disturbances travel at different velocities. The divergence of the waves with increasing sand depth implies that the disturbance was not caused by a double impulse of the hammer on the piston, in which case the disturbances would travel at the same velocity. The difference between the arrival times of the precursor and consolidation phase may be used to approximately calculate their relative velocity. The data used are obtained from Figures 3, 4, 5 and 6 which correspond to separate experiments. The relative wave velocities so obtained are 885, 1100, 1050, and 895 ft/sec. The relative velocity is here defined as the distance between the point of application of the pulse and the pickup, divided by the difference of the arrival times between the precursor and consolidation phase.

When modeling clay was used instead of the sand, a precursor wave was not detected (see Fig. 7 and 8). This implies that the precursor wave is not produced by the instrumentation or the method of applying the impulse.

CONCLUDING REMARKS

(1) There is considerable energy dissipation associated with dynamic consolidation produced by a pulse imparted to dry sand.

(2) The consolidation produced by repeated impacts applied by a hammer release with a fixed potential energy progresses from the source of the impact into the medium.

(3) The energy dissipated by sand confined in a tube, on successive impacts applied by a hammer released with a fixed potential energy, has been accurately measured. The results of these measurements are presented in Figure 2 which shows that the per cent energy dissipated following three or four impacts corresponding to the same level of

potential energy of the hammer, attains a constant value. The asymptotic value is attributed to the energy dissipated by intergranular friction resisting small relative displacements of the grains accompanying the visco-elastic propagation of the disturbances.

(4) A mechanism based upon physical theory governing the propagation of a disturbance imparted to unconsolidated materials is presented. From this mechanism it is inferred that a disturbance is propagated in two principal parts. One consists of a wave of small amplitude anticipating a wave of much higher amplitude propagating at a lower velocity. The first wave is called the precursor and is identified with the visco-elastic deformation of the grains. The second component carrying most of the energy is identified with dynamic consolidation. It is thus concluded that there is probably appreciable attenuation of the second wave and considerably less attenuation of the precursor wave. Further experiments were conducted to check some of these conclusions. The results of these experiments show the composite wave structure predicted from theoretical considerations. The relative velocities between the precursor and consolidation phase have been calculated from data contained in Figures 3, 4, 5 and 6 and are respectively 885, 1050, 895, and 875 ft/sec. The relative velocity is here defined as the distance traveled by the precursor and consolidation phase of the pulse, divided by the difference of their arrival times.

When the intergranular spaces are not sufficiently large to admit dynamic consolidation (grain interpenetration), a disturbance will propagate as an acoustical wave attenuated by the intergranular friction forces accompanying grain deformation. Under these conditions, the granular material will behave visco-elastically and can probably be well represented, mathematically by a Kelvin material.

Whether or not dynamic consolidation to which the precursor phenomenon is here attributed occurs in practice depends upon the initial consolidation of the material and the intensity and magnitude of the disturbance. This observation is supported by the results of the first set of experiments described in this paper.

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Absolute Age of Early Precambrian Rocks in the Bighorn Basin of Wyoming and Montana, and Southeastern Manitoba*

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Abstract—Age determinations on nine samples from the southeastern part of the Beartooth Range, Montana, indicate that the absolute age of the pegmatites and granitic gneisses of this area is 2750 ± 150 m y. A single determination from the northern Bighorn Mountains, Wyoming, suggests a similar age for this portion of the Precambrian basement. Several samples from the Winnipeg River – Johnston Lake area of Manitoba indicate an absolute age of 2650 ± 150 m y for both the pegmatites and gneisses. A similar age was found for a muscovite from the northwestern angle region of Minnesota. Rubidium-strontium ages were found to be more consistent than potassium-argon ages. Argon loss from micas was commonly as great as 15 pct.

Introduction—The measurement of absolute geologic time is necessary in order to define Precambrian Earth history. The recent development of the potassium-argon and rubidium-strontium methods of geochronometry extends the possibilities of measuring absolute ages to a wide variety of igneous and metamorphic rocks. Parts of two presumably early Precambrian areas, the Beartooth uplift of Wyoming and Montana and the Winnipeg River area of southeast Manitoba, were examined using these methods.

This investigation had two objectives: to determine the absolute age of these very ancient areas, and to investigate the magnitude of the natural variations that occur in the apparent ages derived from the A^{40}/K^{40} and Sr^{87}/Rb^{87} ratios.

Symbolically the decay of a given parent to a given daughter isotope can be denoted as follows

$$P_i \xrightarrow{\lambda_i} D_i$$

where λ_i is the decay constant governing the rate at which parent P_i decays to daughter D_i. The age of any geologic system such as a mineral can be determined from D_i/P_i and λ_i, provided the system has been closed to P_i and D_i during its history. Thus, aside from the experimentally determined concentrations of D_i and P_i and the value of λ_i, the assumption that the system is closed must be evaluated.

Unfortunately, no independent criteria to test the assumption of a closed system are available at the present time. The best evidence for this assumption is the agreement of ages determined both on different minerals and by different decay schemes. Thus provided correct decay constants are used, agreement of potassium-argon and rubidium-strontium ages may be interpreted as evidence for a closed chemical system during the history of the mineral. The agreement of ages determined on several minerals from the same geologic unit, varying in grain size and mode of occurrence, is also evidence for the assumption of a closed system. The latter test seems more reliable if a process such as continuous diffusion at room temperature is suspected. Both of these criteria are applied in this study.

In accordance with general usage the term 'age' or 'apparent age' is used for the quantity calculated from a given ratio of D_i/P_i; while 'true age' or 'absolute age' is used to designate the actual period of time which has elapsed since formation of a mineral or rock.

Decay constants—In principle the decay constant of any radioactive isotope can be determined by a direct measurement of the specific activity of that isotope. In the case of U^{238} and U^{235} these constants are known with an accuracy of about 0.5 pct and 2 pct respectively [*Kovarik* and *Adams*, 1941, 1955; *Fleming* and others, 1952]. The values of $\lambda^{238} = 0.154 \times 10^{-10}$ yr^{-1} and $\lambda^{235} = 0.972 \times 10^{-10}$ yr^{-1} are used here.

Measurements of the decay constants of K^{40} have been summarized by *Endt* and *Kluyver* [1954], *Carr* and others [1956], and *Wetherill* [1957]. The average specific activities derived from the first two summaries are 3.4 γ/gm sec, 27.6 β/gm sec; and 3.33 γ/gm sec, 28.6 β/gm sec. *Wetherill* and others [1956] have given a specific gamma activity of 3.24 γ/gm sec derived from A^{40}/K^{40} ratios determined on micas whose age was known independently from lead/uranium ratios on associated uraninites. *McNair* and others [1956] report a value of 3.41 ± 0.06 γ/gm sec and 27.6 β/gm sec. *Wetherill* [1957] reports a value of 3.39 ± 0.15 γ/gm sec. A value of $\lambda_e = 0.58 \times 10^{-10}$ yr^{-1}, based on 3.4 γ/gm sec is used here. The specific beta decay rate is also arbitrarily taken as 28 β/gm sec giving $\lambda_\beta = 4.8 \times 10^{-10}$ yr^{-1}. The abundance of K^{40} is taken as 0.0119 [*Nier*, 1950a].

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Wetherill and others [1956] have shown that for most of geologic time A^{40}/K^{40} ages are more sensitive to λ_e than λ_β. In the age range studied here the uncertainty in the age is 0.4 of that in λ_β and 0.6 of that in λ_e. By a similar argument the uncertainty in the age is approximately half of that in the A^{40}/K^{40} ratio.

Measurements of the specific decay rate of Rb^{87} are summarized by *Flinta* and *Eklund* [1954], and *Ahrens* [1956]. A number of these determinations consistently agree with a half life of about 6.0×10^{10} yr. *Bähnish* and others [1952] suggest that the use of incorrect decay schemes and poor estimates of absorption corrections made this agreement more apparent than real. They indicate that the true half life probably is significantly lower than 6.0×10^{10} yr. *Bähnish* and *Huster* [1954] and *Huster* [1955] report a new determination of the specific activity of Rb^{87}, giving a half life of 4.3 $\pm$ 0.3 $\times 10^{10}$ yr. In a more refined determination Huster and Rausch are reported [*Aldrich* and others, 1956c] to have obtained 4.95×10^{-10} yr. This concurs with the value of 5.0×10^{10} yr derived from a comparison of Sr^{87}/Rb^{87} ratios measured on micas cogenetic with uraninites giving concordant Pb^{206}/U^{238} and Pb^{207}/U^{235} ages [*Aldrich* and others, 1956c]. The corresponding decay constant is 1.39×10^{-11} yr^{-1} which is used in this paper.

The isotopic composition of rubidium reported by *Nier* [1950b] (Rb^{87} = 27.8 pct) is used in this paper.

Experimental techniques—The method of stable isotope dilution was used throughout the present investigation. This technique has been described in a general way by *Inghram* [1954]. *Aldrich* and others [1956a] have described specific techniques for age determinations. The method employed for A^{40} determinations has been described by *Carr* and *Kulp* [1957]. Analyses of strontium, rubidium, and potassium were made on single samples. A tracer consisting of 83.4 pct Sr^{86} was used to determine strontium; 94.6 pct Rb^{87} was used for rubidium analyses; and 99.2 pct K^{41} was employed in potassium analyses. The tracer solutions were calibrated in two ways [*Inghram*, 1954, p. 86]. A first calibration was performed by weighing out known amounts of the tracer salt, for example, Sr^{86} CO$_3$. From the weight, the purity of the salt and the volume of the tracer solution, the concentration of the tracer could be found. A second calibration was performed by adding a known volume of tracer solution to a known amount of a reagent grade salt of the corresponding element (for example, potassium phthalate is used in the calibration of the K^{41} tracer). This mixture was analyzed isotopically. The tracer concentration can then be found from the isotope ratio, the amount of pure salt and the volume of tracer solution used. These calibrations concurred within two per cent with one exception. The concentration of the tracer solutions is thought to be accurate within three per cent. Rubidium and potassium analyses were made on two or five per cent aliquots of the total sample solution.

All mass spectrometric analyses were made on a first order direction focusing, 60° sector field, six-inch radius of curvature mass spectrometer. An ion source similar to that of *Aldrich* and others [1953] was employed. Five to 20 micrograms of strontium oxide derived from strontium perchlorate on a tantalum filament served as a source of Sr^{+} ions. Potassium and rubidium were analyzed together on a tantalum filament previously checked for K and Rb background. In general, isotope ratios could be measured with a standard deviation of less than one per cent.

Discussion of analytical data—A complete summary of analytical data including all replicate measurements is given in Tables 1 and 2. In addition to the concentration of rubidium, normal strontium, radiogenic strontium and potassium, sample weights and isotope ratios needed for age calculations are given. Petrographic, geologic and geographic descriptions of samples are given in the Appendix.

The error on individual concentrations arises from two sources, the mass spectrometric analyses and manipulations involved in the chemical processing of the sample (for example, taking aliquots, adding tracers). The error caused by mass spectrometric analyses is predominant over other errors because it is not directly proportional to the error in the isotope ratio. If A is defined as the total amount of the unknown constituent in the sample, S is defined as the total amount of tracer, and R is taken as the ratio of the tracer isotope to a given sample isotope, it can be shown that $(\partial A/A)/(\partial R/R)$ is usually greater than unity while $(\partial A/A)/(\partial S/S)$ is always unity. The random

TABLE 1 – *Analytical data, rubidium-strontium determinations*

Sample	Sample weight	Rb	Sr (normal)	Sr^{87}	Sr^{87}/Rb^{87}
	gm	ppm	ppm	ppm	
GmYB-11	1.0315	4480 ± 77	1.5	50.1 ± 0.7	0.0395 ± 0.0010
Muscovite	0.4827	4680 ± 97	1.6	52.4 ± 0.7	0.0396 ± 0.0010
GmYB-12	1.000	714 ± 22	96.3	7.91 ± 0.16	0.0392 ± 0.0014
Microcline					
GmYB-5	0.7006	1333 ± 26	6.8	13.36 ± 0.23	0.0354 ± 0.0009
Biotite	1.301	1228 ± 25	...	...	...
	1.0189	1251 ± 19	12.8	12.79 ± 0.18	0.0360 ± 0.0008
GmYB-6	1.0000	837 ± 24	7.2	9.13 ± 0.15	0.0386 ± 0.0013
Microcline					
GmYB-16	0.5028	1345 ± 25	0.9	14.48 ± 0.21	0.0380 ± 0.0010
Muscovite					
GsmYB-17	1.1544	622 ± 10	10.2	7.27 ± 0.10	0.0388 ± 0.0009
GmYB-19	0.8331	342.7 ± 5.9	9.4	3.73 ± 0.063	0.0385 ± 0.0009
Biotite					
GsmYB-20	1.0024	461 ± 8	28.8	5.09 ± 0.09	0.0390 ± 0.0010
Biotite					
GmX-10	0.9653	24,600 ± 690	0.9	264 ± 4.5	0.0379 ± 0.0012
Lepidolite					
GmX-2	0.7273	17,800 ± 350	9.3	190 ± 2.7	0.0378 ± 0.0009
Lepidolite					
GmX-1	1.0001	6080 ± 140	0.2	59.1 ± 0.8	0.0344 ± 0.0009
Microcline	1.2000	6570 ± 150	1.3	58.2 ± 0.8	0.0313 ± 0.0009
GmX-11	1.0037	12,900 ± 270	0.5	135.2 ± 1.9	0.0372 ± 0.0010
Muscovite	0.5994	12,700 ± 210	0.5	134.9 ± 1.9	0.0376 ± 0.0008
GsmX-12	1.0138	453 ± 8	23.7	4.32 ± 0.09	0.0330 ± 0.0009
GsmX-15	0.5303	4730 ± 80	2.01	50.4 ± 0.7	0.0376 ± 0.0008

error arising from measurement of tracer and aliquot volume is taken as one per cent. Errors in the isotope ratio were also taken as one per cent except in a few poor runs where somewhat higher values up to 1.6 pct were assigned. Using these individual errors, the error on the concentration is found from

$$\frac{dA}{A} = \sqrt{\left(\frac{\partial A/A}{\partial R/R}\,\frac{dR}{R}\right)^2 + \left(\frac{dS}{S}\right)^2}$$

For the analyses reported here $(\partial A/A)/(\partial R/R)$ varied from 2.6 to 1.2.

Another estimate of the variance of a single measurement comes from replicate analyses made under identical conditions. The validity of this estimate depends on the number of replicates and the extent to which identical conditions have been maintained. Using the duplicate rubidium analyses given in Table 1 in addition to some taken from unpublished work on the rubidium content of igneous rocks, a standard deviation of 2.0 pct is found. This is in good agreement with the random error found from individual sources of error.

Both the normal strontium concentration and the radiogenic strontium concentration are given in Table 1. The normal strontium in pegmatitic minerals is found to be quite low, especially in the micas. Micas from igneous and metamorphic rocks have a somewhat higher normal strontium content.

Two sources of uncertainty, contamination and errors in isotope ratio, contribute most to errors in the true normal strontium content; both increase sharply in relative magnitude for very low concen-

TABLE 2 – *Analytical data, potassium-argon determinations*

Sample	K^a	Sample weight	Radiogenic A^{40}	Radiogenic A^{40} / Total A^{40}	A^{40}/K^{40}
	pct	gm	ppm		
GmYB-11 Muscovite	8.36^b 8.34 ± 0.25 8.44 ± 0.17	21.1812 4.4735	3.11 ± 0.06 3.05 ± 0.06	0.990 0.987	0.305 ± 0.013 0.299 ± 0.011
GmYB-5 Biotite	6.42 ± 0.12 6.26 ± 0.10	1.7466	2.05 ± 0.05	0.922	0.265 ± 0.012
GmYB-16 Muscovite	8.74 ± 0.18	4.3871	3.35 ± 0.07	0.989	0.315 ± 0.010
GsmYB-17	7.71 ± 0.15	1.4922	2.59 ± 0.05	0.958	0.276 ± 0.010
GsmYB-20 Biotite	5.54 ± 0.14	2.4549	2.15 ± 0.05	0.943	0.319 ± 0.011
GmX-10 Lepidolite	7.81 ± 0.20	15.7965	2.83 ± 0.06	0.990	0.297 ± 0.011
GmX-11 Muscovite	8.50 ± 0.25 9.03 ± 0.17	19.7550	2.94 ± 0.06	0.996	0.275 ± 0.010
GsmX-12 Biotite	5.39 ± 0.10	6.1071	1.58 ± 0.04	0.978	0.240 ± 0.010

[a] Isotope dilution analysis of potassium done concurrently with rubidium analysis, sample weights given in Table 1 apply here.

[b] Different sample than the one used for rubidium-strontium age determination. Analyzed chemically by E. Oslund and C. O. Ingamells, Rock Analysis Laboratory, University of Minnesota.

trations. Because strontium introduced as contamination during processing and normal strontium occurring in the mineral lattice are probably indistinguishable, such contamination has no effect on the concentration of radiogenic strontium. Obviously, if the ratio of radiogenic to normal strontium is high (for example, GmX-10 lepidolite) the uncertainty in the normal strontium has no effect on the radiogenic strontium concentration.

The isotopic composition assumed for the normal strontium, specifically the Sr^{87} abundance, is important in samples having a high normal strontium content. If X is taken as the amount of radiogenic strontium and Y represents the natural isotope abundance of Sr^{87}, this effect is given by $(\partial X/X)/(\partial Y/Y)$. In terms of radiogenic and normal strontium, the differential

$$\frac{\partial X/X}{\partial Y/Y} = -(A/X)Y$$

where A is the amount of normal strontium. The value of Y is very close to 0.07, thus the ratio of normal to radiogenic strontium must be greater than 14 before a one per cent error in isotopic abundance of Sr^{87} results in one per cent error in radiogenic strontium concentration. Actually, the variations found in natural strontium are quite small [*Gast*, 1955, 1956, and further unpublished work]. These studies indicate that the initial isotopic abundance of Sr^{87} in granites and granite pegmatites probably does not vary more than three per cent over the last 3.0 b y. It is concluded that variation in the isotopic composition of the non-radiogenic strontium of the mineral is not an important source of error where radiogenic strontium is greater than 25 pct of common strontium. In the present study all except one sample, that is, microcline, GmYB-12, where radiogenic strontium is 8.5 pct of normal strontium, meet this condition.

The uncertainties given for radiogenic strontium content are then due to the same causes as those in rubidium concentrations. The error in concentrations, due to mass spectrometric analysis, is found from the coefficient $(\partial X/X)/(\partial R/R)$ and the uncertainty in the isotope ratio dS/S is again estimated at one per cent. The error given for the ratio of daughter strontium over parent rubidium is combined from previous errors using the equation

$$\frac{A \pm a}{B \pm b} = \frac{A}{B} \pm \sqrt{\left(\frac{a}{A}\right)^2 + \left(\frac{b}{B}\right)^2}$$

Note that the ratio radiogenic strontium (Sr^{87})/radioactive rubidium (Rb^{87}) is completely independent of sampling variations since these isotopes were determined on the same sample. Errors in potassium analysis are found in the same way as rubidium errors are derived. They are somewhat higher both because the isotope ratios are usually based on fewer scans and because the coefficient $(\partial A/A)/(\partial R/R)$ is often quite high.

The error given on the A^{40} concentrations is derived from replicate analyses made over a period of two years. This experience indicates that the standard deviation for the argon concentrations is from two to four per cent depending on the amount of argon present.

The error in the A^{40}/K^{40} ratio is derived like that in the Sr^{87}/Rb^{87} ratio.

The ages derived from these ratios are given in Tables 3 and 4. When more than one analysis on a given sample was available, the error in the age was diminished by $1/\sqrt{K}$ where K denotes the number of replicate analyses.

TABLE 3 – *Ages from the basement rocks of the Bighorn Basin*

Type of sample and location	Rb-Sr age	K-A age	
	m y	m y	
Muscovite (GmYB-11) Christmas Lake Pegmatite Beartooth Mountains	2800 ± 50	2470 ± 50	
Microcline (GmYB-12) Christmas Lake Pegmatite	2700 ± 100	. . .	
Muscovite (GmYB-16) Blackstone Lake Pegmatite Beartooth Mountains	2700 ± 67	2520 ± 50	
Biotite (GmYB-5) Quad Creek Norite Beartooth Mountains	2530 ± 45	2290 ± 60	
Microcline (GmYB-6) Quad Creek Norite	2730 ± 70	. . .	
Amphibolite, separated Biotite (GsmYB-17) Gardner Lake Area	2750 ± 60	2340 ± 50	
Biotite (GmYB-19) Pegmatite, Shoshone Gorge	2720 ± 65	. . .	
Gneiss, separated biotite GsmYB-20 Northern Bighorn Mountains	2760 ± 70	2540 ± 50	
	Pb^{206}/U^{238}	Pb^{207}/U^{235}	Pb^{207}/Pb^{206}
Uraninite Pegmatite, south of Cooke City, Montana	2600 ± 60	2640 ± 60	2700 ± 20

Discussion—The interpretation and relation of the ages determined in this study to the geologic history of the two areas of ancient rocks will be discussed separately. Absolute ages determined by other methods or workers will be reviewed when they are pertinent.

Bighorn Basin area—The geology of the metamorphic and igneous complex of rocks surrounding the Bighorn Basin has been a subject for more or less continuous field work over the last 50 years [*Darton*, 1906]. Much of this work has been particularly directed at an understanding of the structural features of this rim: see for example, *Bucher* and others [1934], *Chamberlain* [1940], *Thom* [1944, 1947, 1955], *Demorest* [1941], and *Fanshawe* [1939]. These studies were of necessity concerned with events taking place mostly in Laramide Time. *Cloos* and *Cloos* [1934] first suggested that in a broad way, Laramide structures may reflect Precambrian structural trends. Later work seems to support their suggestion [*Lammers*, 1939]. However, it has not been until the recent work of *Eckelmann* and *Poldervaart* [1957] that some of the geologic events of the Precambrian history have been defined. Their detailed study of the Quad Creek area in the Beartooth Mountains suggests the following sequence of events: (1) deposition of an ancient sedimentary sequence; (2) emplacement of gabbro and ultramafic intrusions followed by folding; (3) regional metamorphism and granitization accompanied by pegmatite intrusion and later basaltic dikes; (4) later Precambrian dolerite dikes; and finally, the later Paleozoic and Laramide history referred to above.

The absolute age determinations reported here were made so that Precambrian history described here could be correlated with ancient events evident in other isolated occurrences of Precambrian basement in this area, such as the Bighorn, Wind River, and Owl Creek-Bridger uplifts, and the Cherry Creek and Pony gneisses seen in southwestern Montana.

Previous age determinations from the Bighorn Basin area utilizing radioactive decay have been birefly reviewed by *Eckelmann* and *Poldervaart* [1957]. *Goodman* and *Evans* [1941], report several measurements of the helium index on the Quad Creek norite, giving an age of 1300–1900 m y. Later work on the helium index by *Keevil* [1941] however, has shown that such measurements are

TABLE 4 – *Summary of Rb-Sr and K-A ages[a] from Winnipeg River – Johnston Lake area*

Type of sample and location	Rb-Sr age	K-A age	Source
	m y	m y	
Lepidolite (GmX-10) Silverleaf Claim	2680 ± 90	2440 ± 60	This paper
Lepidolite (GmX-2) Silverleaf Claim	2670 ± 67	...	This paper
Lepidolite Silverleaf Claim	2680 ± 70	...	*Aldrich* and others [1956b]
Lepidolite Silverleaf Claim	...	2270 ± 150	*Cummings* and others [1955]
Microcline (GmX-1) Silverleaf Claim	2340 ± 140	...	This paper
Muscovite Huron Claim	...	2150 ± 180	*Stevens* and *Shillibeer* [1956]
Albite Huron Claim	...	2030 ± 170	*Stevens* and *Shillibeer* [1956]
Muscovite (GmX-11) Pegmatite	2650 ± 45	2340 ± 50	This paper
Biotite Gneiss Sep. Biotite (GsmX-12) Migmatite Zone	2350 ± 66	2160 ± 50	This paper
Muscovite (GmX-15) Northwestern angle pegmatite Minnesota	2660 ± 70	2510	K-A, Goldich (private communication) Rb-Sr this paper

[a] All analyses from other laboratories adjusted to constants used in this paper.

not reliable as absolute ages. This earliest work established that these rocks were early Precambrian but absolute values could not be assigned.

Aldrich and others [1955] and *Wetherill* [1955] have measured some ages on a lepidolite in the Wind River Canyon area. They obtain a rubidium-strontium age of 2460 m y and a potassium-argon age of 2290 m y using the decay constants adopted in this paper.

Table 3 summarizes new age determinations reported in this paper. In addition to the rubidium-strontium and potassium-argon ages measured on micas and feldspars, isotopic ages of a uraninite from a sodic pegmatite ten miles south of Cooke City, Montana, are reported. The agreement among these ages is within experimental error. The pattern is, however, similar to that typically found for uraninites. Assuming that this pattern is due to lead loss the Pb^{207}/Pb^{206} age is closest to the true age. This age is also in best agreement with the rubidium-strontium ages. In any event the absolute age derived from the uraninite and the average rubidium-strontium age are in agreement due to the uncertainty in the Rb^{87} half life.

Specific geographic locations of different areas in which absolute age measurements have been made are shown in Figure 1. Of the four different locations shown on Figure 1 the most detailed study has been in the Beartooth Mountains, particularly in the Quad Creek and Gardner Lake areas. This area was chosen because of the full information available on the geologic environment. *Eckelmann* and *Poldervaart* [1957] have studied the pegmatites in the Quad Creek area and conclude that they are probably synchronous with the regional metamorphism producing the granite. *Harris* [in preparation] has studied the Christmas Lake and Blackstone Lake pegmatites and also concludes that they are probably synchronous with the regional metamorphism. The agreement of the rubidium-strontium age found for the gneissic granite Gsm YB-17 with the pegmatite ages supports this conclusion. It is concluded that the ages reported here represent a single geologic event,

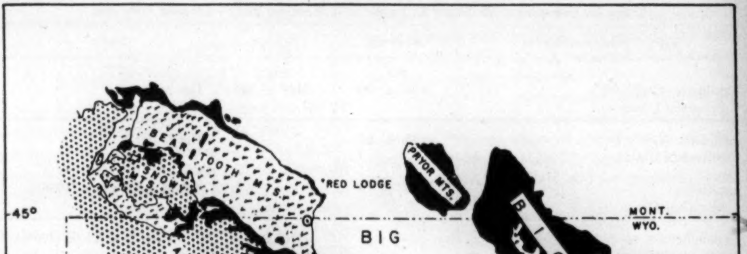
BEARTOOTH MTS.
SNOWY MTS.
RED LODGE
PRYOR MTS.
45°
MONT.
WYO.
BIG
HORN
BASIN
ABSAROKA - SHOSHONE MTS.
CODY
BIG HORN MTS.
44°
LEGEND
TERTIARY VOLCANICS
PALEOZOICS
PRE-CAMBRIAN
LOCATION OF AGE DETERMINATIONS
THERMOPOLIS
OWL CREEK MTS.
BRIDGER RANGE
SCALE
0 20 40
111°
109°
107°

FIG. 1 – Regional Geology of the Bighorn Basin

namely, that of the major regional metamorphism and granitization at about 2750 m y ago.

The measurements given in Table 3 show a high degree of concurrence. Several regularities are evident. First, the potassium-argon ages are consistently lower than the rubidium-strontium ages measured on the same mineral. The differences between the two ages remain rather constant. The explanation of these differences is quite probably some loss of argon from these minerals. With the exception of biotite Gm YB-5 all rubidium-strontium ages measured here agree within the experimental error. Perhaps it is significant that the pegmatite from which this biotite came occurs in a zone of alteration. The biotite sample is within 200 ft of a strongly altered portion of norite. Alteration of the biotite associated with the alteration of the norite seems the most plausible explanation of the low age. The agreement of the other measurements on feldspar and uraninite representing several mineral species, supports the conclusion that the Sr^{87}/Rb^{87} ratio in the muscovite and microcline samples is essentially undisturbed. The possibility of minor alteration such as the loss of one per cent of radiogenic strontium cannot be discounted. Indeed, the possibility of such loses may make the uncertainty in the true age somewhat skewed toward higher ages. The average of seven rubidium-strontium ages is 2750 m y with a standard deviation of 30 m y. Considering possible sources of systematic error and uncertainty in the Rb^{87} half life, the absolute age of the pegmatites and metamorphic rocks must be in the range of 2600 to 2900 m y. However, the relative ages between this and other areas are known more accurately.

Winnipeg River – Johnston Lake area, southeastern Manitoba—During the summer of 1956 a detailed mapping program of the Rice Lake group around the Huron and Silverleaf Claims was begun under the direction of F. D. Eckelmann. It was initiated in part because of the very ancient ages reported by *Nier* and others [1941], *Cummings* and others [1955], *Davis* and *Aldrich* [1953]. A fairly detailed geochronologic study has accompanied the petrologic investigation. The geographic and geologic setting of the area is seen in Figure 2. This map is a portion of the Cat Lake – Winnipeg River map area consisting of metabasalts and metasediments, gneissic granites intruded by pegmatites, and pegmatitic granites. Foliation trends generally ENE. The Silverleaf pegmatite has been described by *Stockwell* [1932]. It is a large-zoned complex pegmatite at least 500 ft long and about 100 ft wide. Lepidolite is found in a core surrounded by quartz and spodumene. It is intruded into a metamorphosed sequence of pillow lavas.

The detailed study of the Winnipeg River – Johnston Lake area (Eckelmann, personal communication) suggests a metamorphic origin for the granite rocks and granite pegmatites of the area. Thus, the age measured here is probably the date of this regional metamorphism. Details of the study leading to this conclusion will be published at a later date.

The three specific locations of samples studied here are shown in Figure 2. They are (1) the Silverleaf pegmatite, (2) a small pegmatite at the contact of the amphibolite and albite granite gneiss, and (3) a sample of biotite granitic gneiss from the migmatite zone. The apparent ages from the present study plus previously reported potassium-argon and rubidium-strontium ages have been summarized in Table 4. The ages reported by *Stevens* and *Shillibeer* [1956] have been recalculated for the decay constants adopted here.

The potassium-argon ages from this area are seen to be consistently lower than the rubidium-strontium dates and furthermore, show a rather large variation even for micas. This discrepancy is interpreted to be due to loss of argon from these minerals. The apparent argon retention of micas ranges from about 70 pct for the Huron Claim muscovite to about 90 pct for lepidolite GmX-10, assuming the true age is 2650 m y. Rubidium-strontium ages on the two different lepidolite samples and one muscovite reported here are in remarkably good agreement. The age reported by *Aldrich* and others [1955] further supports this agreement. The weighted average for these four samples is 2650 m y. The consistency of these

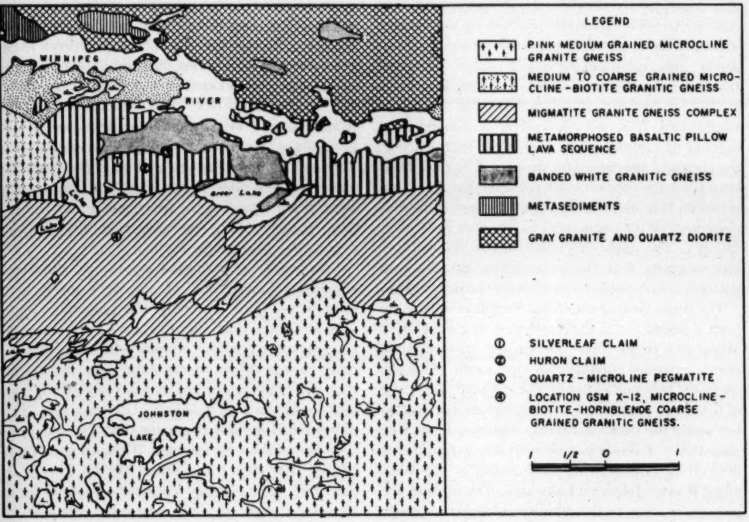
WINNIPEG
RIVER
Greer Lake
Lake
Lake
JOHNSTON
LAKE
Lake
Lake
LEGEND
PINK MEDIUM GRAINED MICROCLINE GRANITE GNEISS
MEDIUM TO COARSE GRAINED MICROCLINE-BIOTITE GRANITIC GNEISS
MIGMATITE GRANITE GNEISS COMPLEX
METAMORPHOSED BASALTIC PILLOW LAVA SEQUENCE
BANDED WHITE GRANITIC GNEISS
METASEDIMENTS
GRAY GRANITE AND QUARTZ DIORITE
① SILVERLEAF CLAIM
② HURON CLAIM
③ QUARTZ - MICROLINE PEGMATITE
④ LOCATION GSM X-12, MICROCLINE-BIOTITE-HORNBLENDE COARSE GRAINED GRANITIC GNEISS.
1
1/2
0
1

FIG. 2 – Huron Claim—Johnson Lake area, southeastern Manitoba

four samples which come from at least three different immediate geologic environments suggests that this represents the undisturbed Sr^{87}/Rb^{87} ratio. The rubidium-strontium ages of microcline from the Silverleaf Claim and of biotite separated from a granite gneiss are significantly lower. These are apparently cases of Sr^{87} loss; the mineral structure and grain size are both factors in a possible explanation of these discordant ages.

The uranium-lead ages on uraninites and monazite from the Huron Claim pegmatite also show quite general discordance [*Nier* and others, 1941]. *Eckelmann* and *Kulp* [1957] have discussed various theories put forth to explain this discordance and conclude that the Pb^{207}/Pb^{206} age is probably minimal due to lead loss in the latter third of the history of the mineral and suggest a probable age close to 2650 m y. The ages found here support the conclusion of lead removal. *Wetherill* [1956] has discussed the problem of open mineral systems and has derived a graphical scheme for finding the time when lead was removed from a uranium mineral. Assuming 2650 m y as the correct age, both uraninites for which complete isotopic data are available suggest that the event resulting in the discordant ages took place 500 m y ago. A general temperature rise in this area at that time is a possible explanation of both the discordant uraninite dates and the apparently low potassium-argon and rubidium-strontium dates discussed below. The importance of detail in geochronologic studies of Archean areas such as this should be emphasized. It is only the variety of minerals and number of samples which give some confidence in the apparent ages found for the area. The rubidium-strontium age appears most trustworthy. The data reviewed here indicate that the true age of the emplacement of the pegmatites in this area is 2650 ± 150 m y. The single determination on the country rock suggests that the surrounding granites and gneisses are contemporaneous with the pegmatites.

The single measurement on a sample of muscovite from a pegmatite in the Northwest Angle region of Minnesota shows that the ancient metamorphic event extended farther to the south. Goldich (personal communication) reports an A^{40}/K^{40} ratio of 0.311 for this sample. This gives an age of 2.51 b y using the decay constants assumed here. The magnitude of the apparent rubidium-strontium is in good agreement with those found in the Winnipeg River – Johnston Lake area. The ratio of the potassium-argon to the rubidium-strontium ages in both localities is also similar. The consistent disagreement between potassium-argon and rubidium-strontium dates suggests some of the potassium-argon dates of 2.4 to 2.5 b y reported by *Goldich* and others [1957] for other rocks in Minnesota could represent rock-forming events which actually occurred 2.6–2.7 b y ago. The Vermilion Range granites and granites as far south as the Minnesota River valley (Sacred Heart granite, Morton gneiss) may then be identical in age with the Laurentian granite gneisses of the Winnipeg River area.

Comparison of Bighorn and Winnipeg River areas—One of the ultimate goals of geochronology is the correlation of geologic events in widely separated Precambrian areas. Such correlations are difficult and often tenuous when based on field studies alone. The geochronologic studies on these two areas present an excellent example for possible correlation of very ancient events. In this regard, it is emphasized that systematic errors such as errors in Rb^{87} half life and possible errors in tracer concentrations are not important when similar ratios, such as Sr^{87}/Rb^{87}, measured under similar conditions, are compared. The average Sr^{87}/Rb^{87} ratio found for concordant samples in the Bighorn Basin area is 0.0389 ± 0.0004, as compared to 0.0377 ± 0.0004 in the Manitoba area. Making the assumption that these samples giving rubidium-strontium ages agreeing within experimental error, represent the true age, the difference between these two corresponds to a time interval of 90 m y, indicating that the basement rocks in the Bighorn-Beartooth area are older than those in southeastern Manitoba and Minnesota. Statistical comparison of the data from these two areas suggests that this difference is real. The probability of the apparent age being the same is less than 0.1. Thus if the assumption regarding the true age is granted, these data suggest that two chronologically distinct events may be involved in these areas.

Comparison of potassium-argon and rubidium-strontium—Comparison of the ages given here shows that quite generally the potassium-argon ages are lower than the rubidium-strontium ages. Comparing only those samples which give apparently correct rubidium-strontium ages, it is found that the potassium-argon ages are about nine per cent lower than the rubidium-strontium ages. The difference is somewhat greater than that reported by other workers for example, *Wetherill* and others [1956]; *Wasserburg* and others [1956]. This is in part due to the decay constants adopted here. However, even if the constants adopted by *Wetherill* and others [1956] are used, the potassium-argon ages are only increased by three per cent;

thus the apparently low potassium-argon ages cannot be completely explained as a result of different decay constants. Three apparently low rubidium-strontium dates were also found. Two of these (GsmX-12 biotite and GmX-1 microcline) are from the southeastern Manitoba region. Along with the discordant uranium-lead dates found at the Huron Claim the discordant potassium-argon and rubidium-strontium ages suggest that this area may have been subject to a later event resulting in these disturbed ages.

The agreement of the Bighorn samples is somewhat better, although very real differences between the potassium-argon and rubidium-strontium ages suggesting argon loss are seen. It seems likely that at least in part this loss of argon may be due to the plutonic or orogenic activity to which this area was subject in late Mesozoic and early Cenozoic time.

The low potassium-argon ages suggest that loss of argon from micas may be more frequent and greater than earlier work has suggested. They further indicate that potassium-argon ages from such old terranes may be subject to severe limitations. They may quite generally be minimum ages. In order to establish absolute ages it appears necessary to compare different mineral systems by the same method as well as using two different methods.

Conclusions—The specific conclusions of this study may be summarized as follows:

(1) The natural variation of most of the Sr^{87}/Rb^{87} ratios measured here is comparable to or less than the experimental variation. Seven out of eight samples from the Bighorn Basin region fall within a range of 3.6 pct, four out of six samples from Manitoba and Minnesota fall within a range of 1.5 pct.

(2) In sharp contrast, the A^{40}/K^{40} ratios vary outside the experimental error. Four samples giving Sr^{87}/Rb^{87} ratios concurring within 3.6 pct give A^{40}/K^{40} ratios varying by 14 pct. This is more than twice the analytical variance. The argon loss of old pegmatitic micas is commonly as high as 15 pct in the two regions studied here.

(3) The absolute age of the major regional metamorphism in the rocks of the Beartooth Mountains of Wyoming and Montana is 2750 ± 150 m y. A single determination in the northern Bighorn Mountains suggests a similar age for these rocks.

(4) The absolute age of the pegmatites and granitic gneisses of the Winnipeg River region of southeastern Manitoba is 2650 ± 150 m y. A single rubidium-strontium determination on a muscovite from the northwestern angle region of Minnesota and the potassium-argon ages of *Goldich* and others [1957], suggest that rocks of this same age may extend well down into Minnesota.

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Appendix—Description of Samples

Gm YB-11 (*LA-11*)—Muscovite from zoned pegmatite near Christmas Lake in the Beartooth Mountains. Exact location of sample is given by *Harris* [in preparation] in the description of this area. The pegmatite is about 100 ft long and 10 ft wide and is essentially conformable. A single book of white muscovite about two inches across was chosen for analysis. Two rectangular pieces 1 × 3 cm were cut from the center of this book. These in turn were cut in half, giving cubes about 1 cm on a side. Two separate analyses were made on two such cubes. Separate argon and potassium analyses were made on quartered samples taken from a batch of muscovite.

Gm YB-12 (*LA-12*)—Tan-gray microcline with a few perthite lamellae from the same pegmatite as Gm YB-11, with no visible inclusions, rather fine exsolution lamellae (0.5 mm). Microscopic examination of powder showed a few large quartz grains.

Gm YB5- (*LA-5*)—Biotite from a small discordant pegmatite within the Quad Creek metanorite. Sample was collected along a roadcut about 500 ft south of the northern intersection of Route 12 and the norite body (see map of *Eckelmann* and *Poldervaart* [1957]). Sample consisted of small intergrown books, the largest plates being no more than a few centimeters across. Some books were closely intergrown with plagioclase. Many surfaces showed a dull light green staining, probably due to chloritization, and some rust colored staining on shiny black mica. Sample taken for analysis was cut from plates chosen for a minimum of staining. However, material analyzed still contained dull and stained surfaces.

Gm YB-6 (*LA-6*)—Pink microcline with some perthite lamellae also from a pegmatite with the Quad Creek metanorite, about 200 ft to the southwest of the biotite pegmatite. Sample has no visible intergrowths. Exsolution lamellae are fractions of a mm in width.

Gm YB-16—Muscovite from discordant pegmatite ½ mile south of Blackstone Lake. Exact location of this pegmatite is given by *Harris* [in preparation]. The pegmatite is unusual for this area in that it contains beryl crystals up to 10 inches long. A single book of muscovite about 4.5 inches across and about 4 inches thick was collected. Samples analyzed came from a part of this book about ¾ of an inch thick. Individual sheets of mica could be peeled from this book. These sheets were partly iron-stained but had regular areas where they were perfectly clear. These clear areas were cut out with a scissors and cut in pieces smaller than 2 cm^2. An 8-gram sample of such material was divided in half. One half was taken for argon analysis. Sample for rubidium analysis was quartered from the remaining half. Sample was collected by Rae L. Harris.

Gsm YB-17(*Z-7*)—Biotite separated from biotite gneiss collected from roadcut on Highway 12 southwest of Frozen Lake. Exact location shown on map of *Harris* [in preparation]. Gneiss contains microcline porphyroblasts up to 2 cm across. Modal analysis showed 33 pct quartz, 20 pct microcline, 41 pct plagioclase, and 5 pct biotite. Biotite shows no evidence of chloritization. Sample analyzed contained more than 95 pct biotite. Description and separation of this sample are the work of R. L. Harris, Dept. Geology, Columbia University.

Uraninite K-156—Collected by A. Poldervaart from an albite, quartz, biotite pegmatite about one mile north of the crossing of Clarks Fork and U. S. 12. This pegmatite surrounds a remnant of amphibolite and is in turn surrounded by granitic gneiss. A small chip weighing about 20 milligrams was selected for analysis.

All of the above samples from the Beartooth Plateau were furnished by A. Poldervaart, Dept. of Geology, Columbia University. Sample numbers in parentheses are those used by *Eckelmann* and *Poldervaart* [1957] and *Harris* (in preparation).

Gm YB-19—Biotite from biotite rich vein in pegmatite. Collected about 500 ft west of Cody Dam in Shoshone Gorge. Biotite was separated from rock using bromoform, individual flakes ranged from 1 to 2 mm across to small fractions of a mm. The sample analyzed was greater than 95 pct mica.

Gsm YB-20—Biotite from a very coarse-grained gneiss, consisting mainly of plagioclase, microcline, quartz, biotite, and hornblende. Several large pieces of this rock were collected from a roadcut along U. S. 14. Approximate location is about the position of the "U. S." on *Osterwald*'s [1955] base map. The rock contained very large porphyroblasts of microcline, some of them over one inch across, and could be described as an augen gneiss. Biotite flakes ranged up to 2 or 3 mm across. Biotite was separated first using heavy liquid techniques (bromoform), then sieving out the fine fraction and finally magnetically using Frantz Isodynamic Separator. The final separate was greater than 95 pct pure biotite, the primary impurities being chlorite and hornblende. The biotite is greenish brown in color.

Gm X-10—Lepidolite from along Winnipeg River, southeastern Manitoba. This sample was taken from a dump at the end of an abandoned tramway from the Silverleaf Claim (now called Bear Claim). Exact location is shown in Figure 2. The sample is identical to new material recently blasted from the claim area. The sample is typical dark lilac-colored, coarse and massive, with individual plates of mica usually 2 to 3 mm across. Some veins of albite were present. Sample for analysis was crushed on an alumina buckboard and muller, then settled in bromoform to remove feldspar and quartz. Only early settling coarse fractions were taken.

Gm X-2—Lepidolite from prospect pit on Silverleaf Claim, southeastern Manitoba. Sample consisted of fine grains of purple lepidolite heterogeneously dispersed through massive dark gray quartz. Several pounds were crushed to about 60 mesh in a jaw crusher and disc pulverizer. Lepidolite was then separated by settling in bromoform. Coarse material sinking in a few minutes was taken for analysis.

Gm X-1—Salmon-colored perthitic microcline, collected from same pit as Gm X-2 lepidolite. Single crystal about 6 inches long was collected. Exsolution lamellae were less than 0.2 mm wide. Several thin veins of white albite cut through the crystal.

Gm X-11—Muscovite collected from quartz-microcline pegmatite about 1500 feet northeast of Huron Claim. This pegmatite is at the contact of a white pegmatitic granite gneiss and metabasaltic pillow lava. The pegmatite is from 5 to 10 ft wide and about 40 ft long. It has both sharply discordant and permeation contacts with the granite gneiss indicating essentially synchronous emplacement of gneissic granite and pegmatite. Sample consists of curved plates of a white mica having a slight metallic luster. Individual books were no more than one cm across. Sample taken for analysis was crushed lightly on an alumina buckboard and muller and sieved to coarser than 60 mesh. The remaining coarse material ranged up to pieces a half cm across.

Gsm X-12—Biotite from a medium- to coarse-grained plagioclase-biotite-hornblende gneiss. Rock specimen is from a lens-shaped gneiss area within a migmatic sequence. The gneiss grades into the migmatite both along and across strike. Such lenses are common in this area. Location of specimen is given in Figure 2. Thin section shows biotite predominating over hornblende, that is, probably growing at the expense of hornblende. Biotite along with other magnetic minerals was separated on a Carpco magnetic separator. Biotite was then separated from other minerals on a Sutton, Steele and Steele Whippet Air Shaking Table. Microscopic examination showed about two to three per cent quartz and feldspar grains and some hornblende. Olive-green biotite makes up more than 95 pct of the sample.

Samples Gm X-2 and Gm X-1 were collected by one of the authors (J. L. K.) during the summer of 1954. The remaining Manitoba samples were furnished by

F. D. Eckelmann, who collected them in the summer of 1956.

Gm X-15—This sample was furnished by S. S. Goldich, Dept. of Geology, University of Minnesota. It consists of small books of white muscovite up to one cm across, and was analyzed as received.

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Discussion of "Evidence for a Critical Wind Velocity for Air-Sea Boundary Processes"

BY HUGO MANDELBAUM

and "Change in the Relationship Between Wind and Surface Water Movement at Higher Wind Speeds"

BY A. L. LAWFORD AND V. F. C. VELEY

[*Trans.*, **37**, 685–693, 1956; **38**, 584–586, 1957]

Hugo Mandelbaum (Wayne State University, Detroit, Michigan; Author's closure)—The discussion by Lawford and Veley centers on the evaluation of the current velocity calculated for wind force 4. By disregarding this value, they point out, a smooth curve could be drawn through all other points (Fig. 5). A similar view was expressed by G. Verploegh in a letter to the author. Verploegh points out that the exceptional value at force 4 appears exceptional only in its *NE*-component. He has plotted the values of Table 4, columns 3, 4, and 10 (Fig. 6). The curves for the *NW*-components and the current directions show a smooth variation. By replacing the exceptional value 10 cm/sec by 8 cm/sec to smooth out the curve of the *NE*-components, we would arrive at 7 cm/sec for the resultant current velocity. This value fits well into the curve drawn by Lawford and Veley (Fig. 5).

Verploegh suggests that the large deviation of the *NE*-component at force 4 may not have a physical cause but might result from a computational error "that unfortunately slipped in somewhere." Lawford and Veley suggest it might be caused by a variation within the statistical material, namely, by a preponderance of winds from the SSW sector which produce stronger currents.

I had not suspected the value at force 4 when I drew the conclusions as presented in my paper. In a statistical investigation we should not discriminate one value against others, unless we want to concede that a statistical approach is futile. A computational error is very unlikely, as a look into Table 3 will show. The values of most NE-components are consistently higher at force 4 than at 5. It is unlikely that computational errors should be so frequent and consistently in the same direction. Unfortunately the punch cards of the original data are at present sorted for a different project, so that it is difficult now to determine how many observations at SSW, SW, and WSW winds were used for the analysis at each wind force. Figure 6b as plotted by Verploegh might suggest a change in wind direction. It shows that at forces 4 and 5 the resultant current has a more northerly direction than at lower and higher wind forces. This might indicate that at forces 4 and 5 SSW winds were more prevalent as Lawford and Veley suggest. However this argument is not conclusive. From Figure 5 of a previous paper [*Mandelbaum*, 1955] it can be seen that winds coming exclusively from the SW sector cause the same directional deviation of the current. At weak and strong winds the currents run with the wind ($\theta = 45°$), while at forces 3 and 4 the direction of the current deviates 10° to the left ($\theta = 35°$). This is a deviation similar to that shown in Figure 6b.

Nevertheless one must agree that the extraordinary value of the NE-component at Beaufort 4 as plotted by Verploegh (Fig. 6a) arouses suspicion when viewed in connection with the smooth curves of the NW-components and the direction deviations (Fig. 6). Even if we cannot give a definite explanation for the exceptional value, one would be justified in placing less statistical weight on it and drawing a curve through all other points as suggested by the discussents (Fig. 5).

Verploegh moreover points out that a discontinuity between Beaufort 4 and 5 could hardly be identical with that proposed by Munk at about 6 cm/sec. Only in the Roll scale would the break lie at this velocity. The other scales place the interval between Beaufort 4 and 5 in the neighborhood of 8 cm/sec. Considering this in connection with a lesser statistical weight put on the value for

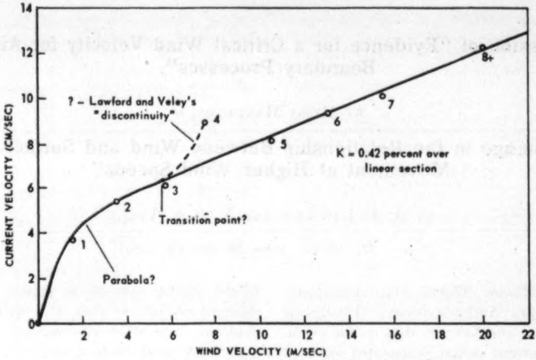

FIG. 5 – Redrafting of Mandelbaum's Figure 1 using Verploegh's scale

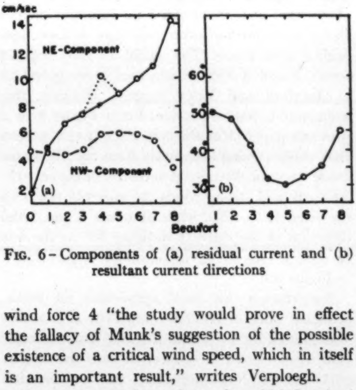

FIG. 6 – Components of (a) residual current and (b) resultant current directions

wind force 4 "the study would prove in effect the fallacy of Munk's suggestion of the possible existence of a critical wind speed, which in itself is an important result," writes Verploegh.

I have to concede another point which Lawford and Veley made, namely, the argument about the constant *c* in the equation $V = kw + c$, which would indicate the existence of a wind-induced current even at calms. The reason for retaining *c* was the following. Table 4 shows that the 'residual current at calms' still contains an influence of the wind velocity. This functional relationship was interpreted as the influence of previous wind situations which are felt more at weaker winds which change their direction more frequently. If the statistical value is still a function of the wind, the constant *c* might represent such a non-eliminated element, and the origin would not be a comparable statistical value. However, spurred by the critical remarks, I tried to find a reliable statistical value for wind force zero. I analyzed 425 observations which were made at wind situations described as calms. These were for some reason not analyzed previously. The NW- and NE-components of the resultant current at calms were found to be 4.71 cm/sec and 1.70 cm/sec respectively. Since these values closely coincide with the 'residual current at calms' for weak winds the difference representing a wind-driven current is practically zero. The origin therefore is another statistical point.

Considering this a parabola accommodates the first four points better than a straight line for all conversion scales except that of Richter. This is one point more in favor of the smooth curve suggested by Lawford and Veley and Verploegh (Fig. 5).

(Editor's note: Figure 5 was prepared by A. L. Lawford and V. F. C. Veley for publication with their discussion which appeared in the August 1957 issue of the *Transactions*, pp. 585–586. It was inadvertently omitted, and so is published here.)

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Discussion of "A Criterion for Selection of Length of Record for a Moving Arithmetic Mean for Hydrologic Data"

BY ROBERT T. BEAUMONT

Trans., **38**, 198-200, 1957

T. E. A. van Hylckama (Laboratory of Climatology, Centerton, New Jersey)—The author has developed a formula "to determine length of record to use to compute a representative moving arithmetic mean to best estimate the next event." I have applied this formula to two sets of 51 random numbers taken from the tables of *Fisher* and *Yates* [1943, p. 90] with the following results:

k:	5	10	15	20	25	30	35	40
φ_1:	868	1044	967	972	1052	1342	1078	952
φ_2:	1026	1060	918	881	853	733	831	1055

From these average error mean square (AEMS) figures, it should be concluded that five 'years' is the best period to predict the next event in the first series and 30 'years' in the second. The random numbers would thus seem to possess a periodicity, but such periodicity is spurious since the numbers are random. Similarly, any apparent periodicity in comparatively short series of 50 years of records of annual streamflow or precipitation are accidental and certainly can give no clue as to the magnitude of the next event.

The fact that the data of precipitation and streamflow are random is further indicated by the individual AEMS's. The k values range from ten for Spokane, Washington, and Laramie, Wyoming, to 35 for Cheyenne, Wyoming, and to deduce from the composite graph (Fig. 4) that 20 years is the best period seems a fallacious conclusion. Moreover, whereas a correlation can usually be established between annual precipitation and streamflow, and although such correlation at times may fail due to extraordinary hot or cold seasons or unusual intensities of rainfall, it is most unlikely that even if precipitation would show a periodicity of 20 years, streamflow would show a 'best period' of 15 years.

A closer study of the AEMS formula shows that the magnitude of the AEMS is determined by the precipitation or runoff data of the last $(n - k)$ years in the observed series. If these years happen to have a small variability with a mean close to the average mean of the sets of k years, the AEMS will be small. If, on the other hand, these last years contain extremes the AEMS will be high. Since yearly precipitation data show rarely, if ever, any persistency or definite periodicity even over periods of a hundred and more years [for example, *Rosenan*, 1955; *Labrijn*, 1945; *Brooks* and *Carruthers*, 1953] the AEMS is a random number taken from random data and cannot possibly be indicative of future events.

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ROSENAN, N., One hundred years of rainfall in Jerusalem, *Israel Exploration J.*, **5**, 137-153, 1955.

Robert T. Beaumont (U. S. Soil Conservation Service, Portland, Oreg., Author's closure)—The analysis made by van Hylckama is most interesting and I appreciate his interest in my work. The results he obtained by using two sets of random numbers are parallel to some of my earlier efforts. However, our interpretation of results differ.

van Hylckama's syllogism that computation of the average error mean square has no value for precipitation and runoff records because its computation on two random series resulted in low values of AEMS for k equal to 5 and 30 years, overlooks one important aspect of the problem. That is to make an analogy between results computed from random numbers and results computed from physical climatic records.

van Hylckama does not make clear why a single period for k should correspond to the lowest value for AEMS when using random numbers. One would expect, and the results we have obtained to date confirm, that there is no single period for k which correspondingly has the lowest AEMS value for a random series.

There is merit in van Hylckama's comments on the composite graph (Fig. 4) for there is always some risk in interpretation of results drawn from a small population as aptly demonstrated by his conclusion from the two series of random numbers. Reference to this aspect of the problem was treated in my article (p. 199) as follows: "A great many more computations of AEMS should be made on similar climatological and hydrological data to ascertain if the 15–20 year is the best period, or whether there are other periods which give a lower AEMS. These data should be examined to see if there are other parameters by which they could be classified, (that is, climatic parameters)." Similarly, if AEMS values could be computed from a large series of random numbers, some basis for comparison and testing of the AEMS between the random numbers and the physical climatic records should evolve.

Reviews, Abstracts, and Bibliography

Reviews and Abstracts

FELIX CHAYES, *Petrographic modal analysis—An elementary statistical appraisal*, John Wiley & Sons, xii + 113 pp., 1956, $5.50.

Chayes' detailed study of the modal analysis of rocks has extended over a considerable period of time. This book contains an interpretation of his work. It is, by itself, a distinct contribution to quantitative petrography. Chayes first proves the fundamental area-volume relationship which he calls the "Delesse relation." He states it thus: "Thus, the ratio of the area occupied by mineral A to the area occupied by all minerals (the total measurement area) is a consistent estimate of the volume percentage of mineral A in the rock."

Six of the remaining chapters represent a statistical study and an interpretation of the data for a series of granites which he has carefully studied. Using these data, Chayes evaluates and describes: (a) the reproducibility of thin-section analyses; (b) identification and tabulation conventions; (c) analytical error in modal analysis; (d) effect of grain size and area of measurement on analytical error; (e) a measure of coarseness in the granitic fabric; and (f) control of analytical error by replication.

Modal analysis of banded rocks is critically examined and positive recommendations on how to handle this type of measurement are given. The "Holmes effect" concerns the overestimation of opaque minerals in transmitted light. That is, the area measured is always that of the maximum cross section in the thin section rather than the true area which is the area at the surface of the thin section. Chayes has examined this effect analytically and has prepared a table of correction factors for measurements.

This book should be read by all petrographers making modal analyses. It will be also of much value to scientists interested in statistical methods in geological studies.

GEORGE T. FAUST

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Notes and Personalia

Notes

SUMMER COURSE ON AIR POLLUTION AT MASSACHUSETTS INSTITUTE OF TECHNOLOGY—Massachusetts Institute of Technology has announced a special summer course dealing with the causes, control, and effects of air pollution to be held in Cambridge, August 11–22, 1958. Details may be secured by writing to James M. Austin, Director of the Summer Session, Room 7–101, Massachusetts Institute of Technology, Cambridge 39, Massachusetts.

NEW COURSE ON THE STUDY OF AIR POLLUTION AT THE UNIVERSITY OF NORTH CAROLINA—The School of Public Health at the University of North Carolina has announced a graduate course on Air Pollution in connection with the work in the Department of Sanitary Engineering. This will be given under a grant from the Community Air Pollution Program of the U. S. Public Health Service by Lyman A Ripperton, recently of the Los Angeles Air Pollution Control District, and Emil T. Chanlett.

NINTH ALASKAN SCIENCE CONFERENCE—The Ninth Alaskan Science Conference will be held at the University of Alaska, September 2–5, 1958. This will cover a broad spectrum of science and that portion relating to geophysics is under the Chairmanship of Christian T. Elvey, Geophysical Institute, University of Alaska, College, Alaska.

SCIENTISTS AND ENGINEERS IN RESEARCH AND DEVELOPMENT—A recent release of the National Science Foundation (NSF-58-9) notes that 230,000 scientists and engineers, military and civilian, were engaged in a wide range of organizations in the natural sciences, including engineering, in 1954. These researchers involved an expenditure of approximately $5.4 billion. The analysis indicates that about 30 per cent were engaged in physical sciences, 60 per cent in engineering, and 10 per cent in life sciences. The analysis shows that about 166,500 were working for industry-oriented organizations, 35,300 in Federal Government work, 25,200 in colleges and universities, and 2000 in other institutions.

SALARY STATUS OF FEDERAL SCIENTISTS—The U. S. Civil Service Commission, recognizing the importance of the role of scientists in the work of the Federal Government, has advanced the salary status of certain scientists to the top of the grade for the appropriate positions. This covered certain phases of geophysical science but not others, and in the case of meteorology, those who are categorized in some branch of physics received the increase but those who are characterized as meteorologists did not.

CURTAILMENT OF PLANS FOR THE *ATLANTIS*—The Woods Hole Oceanographic Institution announces that because of engine trouble the eight-month cruise of the research vessel *Atlantis* has had to be curtailed severely and the vessel has been laid up in New York for repairs. The *Atlantis* was scheduled to make observations on the physical and chemical characteristics of the Brazil Current along a line from Buenos Aires to Capetown, taking sediment cores from the ocean bottom. From Capetown the ship was to proceed to the Indian Ocean for work with the *Vema* of Lamont Geological Observatory there. It is now the plan that, upon completion of the repairs, the *Atlantis* will proceed by the most direct route to the Indian Ocean.

The contemplated work in the South Atlantic has been temporarily postponed and will probably be made by the research vessel *Crawford*.

COOPERATION BETWEEN THE WEATHER BUREAU AND THE FEDERAL CIVIL DEFENSE ADMINISTRATION ON MEASURING FALLOUT RADIATION—Plans have been announced of the establishment of nationwide facilities to measure fallout radiation at 260 Weather Bureau observatories located throughout the nation. This is especially designed to be useful in the event of a thermonuclear attack. This will bring the total number or monitoring facilities up to about 700.

SCOT EXPEDITION OF SCRIPPS INSTITUTION OF OCEANOGRAPHY—The Scripps Tuna Oceanography Research group will join with the Inter-American Tropical Tuna Commission on an expedition to the Eastern Tropical Pacific, April 28 to July 7, 1958, using the research vessel *Spencer F. Baird*. The work will extend along the western coast of North America from San Diego to Panama.

NEW JOURNAL ON THE *PHYSICS OF FLUIDS*—The American Institute of Physics has announced the publication of a new journal entitled *The Physics of Fluids*, the first number released in January-February, 1958. Inquiries should be addressed to the Institute at 335 East 45th Street, New York 17, New York.

GRANTS OF THE NATIONAL SCIENCE FOUNDATION—During the quarter ending December 31, 1957, the National Science Foundation made 409 grants totaling $15,000,000 in support of various aspects of science. During the previous quarter, 316 grants were awarded totaling about $5.5 million.

ANTARCTIC ICE DRILLING—Deep drilling of the Antarctic Ice at the IGY Byrd Station in the Antarctica reached the 1000-ft mark on January 26. The ice cores from the drill hole are removed by compressed air especially cooled to avoid melting of the snow. By means of ice cores the annual layers supply clues to the Antarctic climate reaching back many centuries. It is estimated that the snow accumulations at this site are at only about half the rate of those on Greenland, and, as a consequence, the 1000-ft level at the Byrd Station is approximately equal to the age of ice at the 2000-ft level in Greenland.

NEW MARINE MICROBIOLOGICAL LABORATORY—The Institute of Marine Science of the University of Texas has recently established a section on marine microbiology under the direction of Carl H. Oppenheimer. The Institute is situated on Mustang Island at Port Aransas, 25 miles north of Corpus Christi.

CONFERENCE ON ELECTRONIC STANDARDS AND MEASUREMENTS—A Conference on Electronic Standards and Measurements will be held at the Boulder Laboratories, National Bureau of Standards, August 13–15, 1958. Questions concerning this should be addressed to the Secretary-Treasurer of the Conference, James F. Brockman, Boulder Laboratories, National Bureau of Standards, Boulder, Colorado.

NEW IGY STAMP—The Government of the United States plans the issuance of a special postage stamp, honoring the International Geophysical Year. This follows the lead of many other nations. The Canadian stamp was issued on March 5, 1958. The U. S. stamp is scheduled for release on May 31, 1958.

SEVENTH INTERNATIONAL INVENTORS EXHIBITION—This Exhibition will be held in Brussels, June 6–29, 1958, in relation to the World's Fair being held during the summer months in Brussels. The official correspondent for the United States is Otto A. Witt, P. O. Box 1481, Milwaukee 1, Wisconsin. Fifteen categories have been established for the Exhibition.

MESOSCALE ANALYSIS AND FORECASTING—A three-day workshop devoted to mesoscale weather phenomena was held in Washington, D. C., March 3–5, 1958, under the sponsorship of the D. C. Branch of the American Meteorological Society, under the Chairmanship of Carl Reber. The speakers from out of town included James Austin, Massachusetts Institute of Technology; A. K. Blackadar, Pennsylvania State University; C. F. Chappell, U. S. Weather Bureau, Severe Local Storms Forecasting Center; Tetsuya Fujita, University of Chicago; M. G. H. Ligda, Texas A and M College; and R. G. Miller, The Travelers Insurance Companies.

FORTIETH ANNIVERSARY OF THE POLAR FRONT THEORY—The Norwegian Geophysical Society is holding a meeting in Bergen, Norway, June 19–25, 1958, to commemorate the Fortieth Anniversary of the Polar Front Theory. This will be essentially a meeting of the meteorologists with general circulation, cloud physics, and weather forecasting as themes of various sessions. The American Meteorological Society is formally participating in the meeting.

STATUS OF MAPPING IN THE UNITED STATES—New indexes of maps showing the status of topographic mapping and the status of aerial photography in the United States are now available from the U. S. Geological Survey Mapping Information Office, Washington 25, D. C.

Personalia

LESLIE F. BAILEY of the U. S. Coast and Geodetic Survey has been given the silver medal of the Department of Commerce for meritorious service.

WERNER A. BAUM, Professor of Meteorology at Florida State University, has been designated for the position of Director of University Research. Seymour L. Hess, who devoted the first semester to study at New York University is now Head of the Department of Meteorology at Florida State University.

DETLEV W. BRONK, President of the National Academy of Sciences, Chairman of the National Science Board, and President of the Rockefeller Institute for Medical Research, has been awarded the Gold Medal of the International Benjamin Franklin Society.

JAMES E. CASKEY, JR., of the U. S. Weather Bureau, has been given the silver medal of the Department of Commerce for meritorious service.

R. CORDAY COUNTS, Meteorologist in Charge, U. S.

Weather Bureau, San Francisco, and Secretary of the Pacific Southwest Regional Committee of AGU, has been elected a member of the Council of the American Meteorological Society.

Joe R. Fulks, Meteorologist in Charge, U. S. Weather Bureau Forecast Center, Chicago, has been elected a member of the Council of the American Meteorological Society.

Paul M. Fye, until recently Associate Technical Director for Research at the Naval Ordnance Laboratory in Silver Spring, Maryland, has been appointed Director of the Woods Hole Oceanographic Institution, succeeding C. O'D. Iselin, who had served as Director from 1940 to 1950 and from 1956 to 1958.

Ross Gunn has left his position as Director of Physical Research for the U. S. Weather Burean to accept an appointment as Visiting Research Professor of Physics at American University to work under a contract which the University has with the Atomic Energy Commission on their Nuclear Fusion Power Program. He has completed more than thirty years of positions of responsible scientific and research leadership in the Naval Research Laboratory and the Weather Bureau.

Charles Sumner Heidel, Staff Engineer, Water Resources Division of the U. S. Geological Survey in Montana, has recently retired after 47 years of service with the State and more recently with the U. S. Geological Survey. He had been with the Geological Survey since 1930.

Henry G. Houghton, Professor of Meteorology and Director of the Inter-Departmental Laboratory of Earth Sciences at Massachusetts Institute of Technology, was recently given the American Meteorological Society's Award for Outstanding Services.

C. O'D. Iselin has retired as Director of the Woods Hole Oceanographic Institution but will continue to be associated with it as the first Henry Bryant Bigelow Oceanographer, a Chair recently founded by the Board of Trustees of the Institution.

C. E. Jacob, Groundwater Consultant, has moved his headquarters from Orem, Utah, to Northridge, California, a suburb of Los Angeles.

Ellis A. Johnson, Director, Operations Research Office, of Johns Hopkins University, has been awarded the Army's Distinguished Civilian Service Medal "for his distinguished ability and performance."

Ralph H. King has been appointed Associate Professor of Geology at the University of Kansas and Geologist and Technical Editor for the Kansas State Geological Survey.

Julian W. Low, Research Geologist for the California Company, has written a manual of *Geologic field methods*, a companion volume to his book on *Plane table mapping*. The publisher is Harper and Brothers of New York.

Thomas F. Malone, Director of Research for The Travelers Insurance Companies in Hartford, Connecticut, and Vice President of the Section of Meteorology of AGU, has been re-elected Secretary of the American Meteorological Society.

John F. Mann, Jr., formerly Associate Professor of Geology at the University of Southern California, has organized a group of consultants on groundwater problems with headquarters at La Habra, California. The group is operating under the name of John F. Mann, Jr., and Associates, Consulting Groundwater Geologists.

Aden B. Meinel has been appointed Director of the new National Astronomical Observatory, which is under the direction of the Association of Universities for Research in Astronomy, under contract with the National Science Foundation. The site selected for the new Observatory is in Arizona. Meinel has been on leave from Yerkes and McDonald Observatories since the inception of the National Astronomical Observatory project and has served as full-time Executive Secretary to the Advisory Panel of the National Science Foundation.

James H. Nelson of the U. S. Coast and Geodetic Survey has been awarded a gold medal by the Department of Commerce for his exceptional service.

Sverre Petterssen, Professor of Meteorology at the University of Chicago, has been elected President of the American Meteorological Society.

Austin C. Poling of the U. S. Coast and Geodetic Survey has been given the silver medal of the Department of Commerce for meritorious service.

Alfred C. Redfield, Senior Oceanographer Emeritus of Woods Hole Oceanographic Institution, has been presenting Sigma Xi lectures at various colleges and universities during the winter months on the subject "The Proportions of Things in the Sea."

William Shofnos of the U. S. Coast and Geodetic Survey has been given the silver medal of the Department of Commerce for meritorious service.

Harold C. Urey, Distinguished Service Professor of Chemistry at the Enrico Fermi Institute of Nuclear Studies at the University of Chicago, soon to undertake duties at the University of California, has recently been awarded an honorary doctorate by Wayne State University.

Ernest H. Volwiler, President and General Manager of Abbott Laboratories, has been designated as Chairman of the Division of Chemistry and Chemical Technology of the National Academy of Sciences–National Research Council to succeed Frederick D. Rossini on July 1, 1958.

Harry Wexler, Director of Meteorological Research for the U. S. Weather Bureau, has been awarded a gold medal by the Department of Commerce for his exceptional service.

J. Tuzo Wilson, Professor of Geophysics at the University of Toronto, and President of the International Union of Geodesy and Geophysics, has been delivering a Sigma Xi lecture at a number of colleges and universities during the winter months on the subject "Geophysics and Continental Evolution."

M. Gordon Wolman of the Water Resources Division of the U. S. Geological Survey has accepted an appointment as Chairman of the Department of Geography at Johns Hopkins University and will assume his new post as Associate Professor on July 1 1958. He will continue on a part-time basis with the Geological Survey.

Henryk Arctowski, Meteorologist and Geologist, died February 20, 1958, at the age of 86. He was born in Warsaw, Poland, and studied at the University of Lwow, University of Zurich, and the Sorbonne. Dr.

Arctowski had an outstanding career in meteorological and climatological studies in Poland and came to the United States in the fall of 1939 to attend the Seventh General Assembly of the IUGG. While he was here, his country was overrun by the Germans and the Russians, and he never returned to Poland. He left behind a library of some 20,000 volumes at the library of Lwow where he was Professor and Head of the Department of Climatology. He continued his work in the United States as a Research Associate with the Smithsonian Institution, retiring about six years ago. He had been a member of the American Geophysical Union since 1943.

David Whitcher Mann, President, David W. Mann, Inc., manufacturer of custom-made precision instruments, died July 2, 1957, at the age of 69. He was born at Medford, Massachusetts, studied at Dartmouth College, 1910–1914. He began work in the Astronomical Laboratory of Harvard University in 1914 where he continued until 1919. From 1919 until 1947, he worked at the Jefferson Physical Laboratory at Harvard. At that time he established his own plant as a designer of custom-made precision instruments. He had been a member of AGU since 1934.

Edmund Schulman, Associate Professor of Dendrochronology at the University of Arizona and also with the University's Tree-Ring Laboratory, died January 8, 1958, at the age of 49. He was born in Brooklyn, New York, and took his bachelor's degree at the University of Arizona in 1933 and his master's degree from the same institution in 1935. He received a second master's degree from Harvard in 1938, and a doctorate in 1944. He worked at Harvard's Blue Hill Observatory in 1938, and then took up duties with the Tree-Ring Laboratory at the University of Arizona and in the Department of Dendrochronology, which he continued until the time of his death. He was a recognized world-wide authority on dendrochronology. He became a member of AGU in 1945.

Harry Oscar Wood, world-renowned seismologist, one of the founding members of the American Geophysical Union, and founder of the Seismological Laboratory of California Institute of Technology, died in Pasadena, February 4, 1958, at the age of 78. He took his baccalaureate degree from Harvard in 1902 and his master's degree from Harvard in 1904. While studying for his master's degree, he was an Assistant in Mineralogy and Petrography at Harvard. From 1904 until 1912, he did work in Mineralogy and Geology at the University of California, when he began research work in seismology at the Hawaiian Volcano Observatory where he worked until 1917. Following a period of work as Assistant Secretary of the National Research Council, he became a Research Associate in Seismology at the Carnegie Institution of Washington, on which he was engaged from 1921 until his retirement in 1942. He served as the first General Secretary of the American Geophysical Union from 1919 until 1921.

Report of the Committee of Tellers

The Committee of Tellers met in the Board Room of the AAAS Building, in which building is the office of the American Geophysical Union, at 09h on February 5, 1958 to count ballots. The following assortment of ballots was considered:

Total ballots received		1575
Rejected ballots:		
Ballots postmarked or received late or both	18	
Ballots from non-citizens of the United States	13	
Defective ballots (unmarked, or intent of voter not clear)	4	35
Qualified ballots tabulated		1540

The proposed amendments to the Statutes were adopted, reading as follows:

(1) Amend the first paragraph of Article 4 as follows:

Article 4: Sections—The American Geophysical Union shall consist of Sections as follows: (a) Geodesy; (b) Seismology; (c) Meteorology; (d) Geomagnetism and Aeronomy; (e) Oceanography; (f) Volcanology, Geochemistry, and Petrology; (g) Hydrology; (h) Tectonophysics.

(2) Amend the first paragraph of Article 5 of the Statutes to read:

Article 5: Officers of the American Geophysical Union—The officers of the American Geophysical Union shall consist of a President, a Vice President, and a General Secretary, whose terms of office shall expire June 30, 1947, but terms of office effective July 1, 1947, shall be for periods of three years, with the limitation that the President and Vice President shall not be eligible for immediate re-election; in case any office, except that of President, becomes vacant, the Executive Committee of the Union shall designate a successor in office to complete the term. In the case of the death of the President, the Vice President shall automatically become President. These officers shall be elected by mail ballot.

(3) Amend paragraph (d) of Article 3 of the Statutes as follows:

(d) *Associates*—(1) Citizens of the United States of America other than those eligible for regular membership under Article 3, Sections (a) or (b), whose interest in Geophysics is deemed by the Executive Committee of the Union to warrant their election. Associates shall enjoy the privileges of Members except that they may not be officers of the Union or of the Sections, or be delegates of the Union at International Assemblies or Meetings.

(2) Nationals of other countries having the same qualifications, elected by the Executive Committee of the American Geophysical Union; these may not vote or be officers of the Union or of its Sections, or delegates of the Union to International Assemblies or Meetings.

The tally of the ballots was as follows:

Amendment 1	Votes for	1486
	Votes against	48
Amendment 2	Votes for	1521
	Votes against	16
Amendment 3	Votes for	1500
	Votes against	30

One 1956 ballot was received voting for the officers of the union and its several sections. It was not considered a qualified ballot.

The members of the Tellers Committee, appointed by President Ewing upon nomination of the Committee Chairman, are: Bernard D. Zetler, Coast and Geodetic Survey; James N. Jordan, Coast and Geodetic Survey; B. C. Byrnes, U. S. Hydrographic Office; R. W. Seaton, U. S. Hydrographic Office; H. G. Thomasson, U. S. Geological Survey; Robert Guillou, U. S. Geological Survey; and G. E. Manger, U. S. Geological Survey.

J. H. Nelson, *Chairman*
Committee of Tellers

Nominating Committee of the Pacific Northwest Region—Norbert Leupold, Chairman of the Pacific Northwest Regional Committee, has announced the designation of Hollis N. Orem of the U. S. Geological Survey in Portland as Chairman of the Committee on Nominations for the next triennium. The other two members of the Committee are David Rockwood of the Corps of Engineers, 808 S. W. Briar Lane, Portland 1, Oregon, and Robert Beaumont of the Soil Conservation Service, 209 S.W. 5th Avenue, Ross Building, Portland 4, Oregon.

Special Announcements

Reprinting of Back *Transactions*—Volumes 1–12 of the *Transactions* (1920–1931) have been reprinted by the Johnson Reprint Corporation (excepting Volumes 3 and 5, which were mimeographed minutes only). Prices range from $4.50 to $15.00 a volume, with $80.00 as the price for the total set. Interested persons should get into touch with the Johnson Reprint Corporation, 111 Fifth Avenue, New York 3, New York.

There is also the plan to publish more recent out-of-print volumes, this depending in large measure upon the apparent market for these. Write concerning your interest to the Johnson Reprint Corporation.

Symposium on the Physics of Ice Movement—The International Association of Hydrology, IUGG, is arranging a Symposium on the Physics of Ice Movement to be held at Chamonix-Mont Blanc, France, September 16–24, 1958. Participants from the United States should forward their communications to C. C. Warnick, Engineering Experiment Station, University of Idaho, Moscow, Idaho, for consideration for inclusion in the program. Those from other countries should get into touch with their national group or with the International Secretary, Prof. L. J. Tison, rue des Ronces 61, Gentbrugge, Belgium.

Pacific Northwest Regional Meeting to be held in Portland, Oregon, November 13–14, 1958—The Pacific Northwest Regional Committee has selected Portland, Oregon, for the site of its meeting this coming autumn, November 13–14, 1958. Interested persons should get into touch with the Chairman of the Regional Committee at present, Norbert Leupold, Leupold and Stevens Instruments, Inc., P. O. Box 5082, Portland 13, Oregon, or the Secretary-Treasurer of the Region, Franklin I. Badgley, Department of Meteorology, University of Washington, Seattle 5-Washington. The new officers for the Regional Committee with terms beginning July 1, 1958 are: Chairman, Wilbur D. Simons, and Secretary-Treasurer, Vail Schermerhorn.

NATIONAL ACADEMY OF SCIENCES

Number 9 • March 1958

IGY BULLETIN

A monthly survey by the U. S. National Committee for the International Geophysical Year. Established by and part of the National Academy of Sciences, the Committee is responsible for the U. S. International Geophysical Year program in which several hundred American scientists are participating and many public and private institutions are cooperating.

First US-IGY Satellite

The first US-IGY satellite, 1958α, was launched from Cape Canaveral, Florida, at 10:48 pm EST on January 31, 1958.

Launching: The launching vehicle was a four-stage modified Jupiter-C rocket developed jointly by the US Army Ballistic Missile Agency and the Jet Propulsion Laboratory (JPL) of the California Institute of Technology. The first stage was a modified Redstone rocket with liquid propellants. The second and third stages were composed of clusters of solid propellant rockets, each forty inches long and six inches in diameter.

The upper stages of the rocket were spin-stabilized in order to minimize variations in the direction of travel owing to possible faulty alignments of rocket thrust and unbalance of the assembly. Electric motors were used to spin the upper stages at 450 rpm before take-off. After take-off the spin was increased to 700 rpm.

The over-all length of the composite vehicle is 823.3 inches. The first stage, 672.8 inches long and 70 inches in diameter, separated from the upper section at an altitude of 53 miles, when its fuel was expended, and fell into the Atlantic. The upper stages coasted to an altitude of 230 miles. At the apex of the arc, when the rocket's path was approximately horizontal, the high-speed stages were fired in sequence, increasing the orbital speed of the satellite to approximately 18,000 mph.

Satellite Characteristics: The final stage of the Jupiter-C, which carries the scientific instrumentation, is 80 inches long, six inches in diameter, and weighs 30.80 pounds after burnout (see Fig. 1). The instrument payload, carried in the forward section, weighs about 11 pounds. The protective instrument case of stainless steel weighs 7.5 pounds with an inner liner of fiber glass. The forward part of the instrument case is painted with stripes of aluminum oxide, designed to control the radiative properties of the surface and maintain the interior at a reasonable temperature. Four whip-like antennae extend from the midsection of the satellite.

Instrumentation: The satellite carries instrumentation to measure the total cosmic-ray intensity, density of meteoric matter in the satellite's orbit, and measurements of temperature both within and at the skin of the satellite.

Cosmic rays are measured by a Geiger counter. The impact of solid meteoritic particles is measured in two ways: by a microphone which picks up the actual sound of particles hitting the satellite shell, and by erosion gauges which change their electrical characteristics when broken or eroded by contact with small particles.

Thermal probes measure the temperature in the interior of the satellite and next to the outside skin.

Two radio transmitters are carried. One

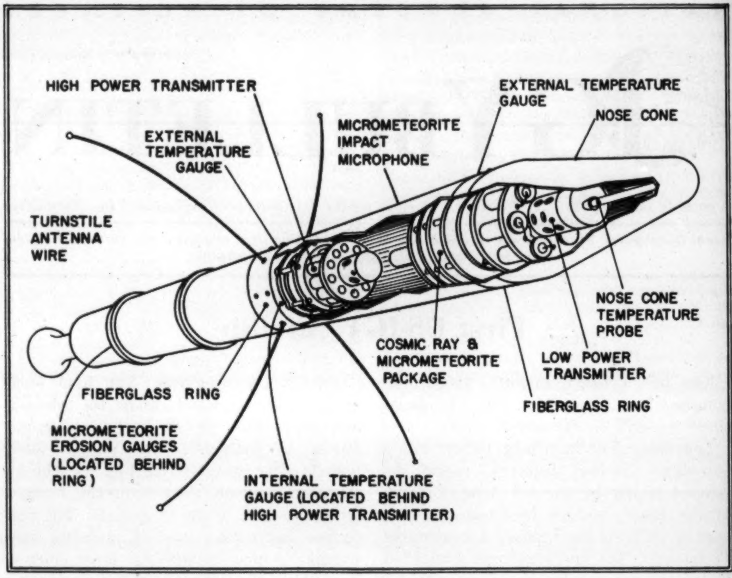

HIGH POWER TRANSMITTER
EXTERNAL TEMPERATURE GAUGE
MICROMETEORITE IMPACT MICROPHONE
EXTERNAL TEMPERATURE GAUGE
NOSE CONE
TURNSTILE ANTENNA WIRE
NOSE CONE TEMPERATURE PROBE
COSMIC RAY & MICROMETEORITE PACKAGE
LOW POWER TRANSMITTER
FIBERGLASS RING
FIBERGLASS RING
MICROMETEORITE EROSION GAUGES (LOCATED BEHIND RING)
INTERNAL TEMPERATURE GAUGE (LOCATED BEHIND HIGH POWER TRANSMITTER)

Fig. 1. *US Earth Satellite 1958α. Satellite consists of final stage of rocket vehicle with scientific and telemetry instruments.*

radiates approximately 60 mw of power on 108.030 mc. This transmitter ceased operating during the 12th day of orbit and unexpectedly resumed transmission on February 24th. The other transmitter, radiating 10 mw of power on 108.000 mc, the primary tracking frequency, is designed to operate for approximately two months. Both transmit telemetry data on instrument readings. (A detailed description of the telemetry system was given in *Bulletin No. 8.*)

Observations: The two US radio observation nets, the prime system, Minitrack, and a supplemental system, Microlock, have tracked the satellite and have received telemetry data on every pass. The Minitrack stations utilize comparison of the phase of 108.000-mc signals arriving at different antennas to obtain the angular altitude and azimuth of the satellite. Seven Minitrack stations are stretched approximately along the 75th meridian in a "picket fence" from Blossom Point, Maryland, to Santiago, Chile. Other Minitrack stations are located at Antigua, in the Caribbean; San Diego, California; and Woomera, Australia (see *Bulletin No. 2* for a more complete description of Minitrack). The Microlock stations are at Cape Canaveral, Florida; Ibadan, Nigeria; Singapore; Earthquake Valley near San Diego, California; and Temple City, California. The stations at Ibadan and Singapore are used for telemetry only.

Although visual observations from the United States were not expected, a telescopic sighting was reported by a Moonwatch team at Alamagordo, Mew Mexico, on Saturday, February 1, and a naked-eye sighting by a Moonwatch team in Manhattan, Kansas, on Sunday, February 2.

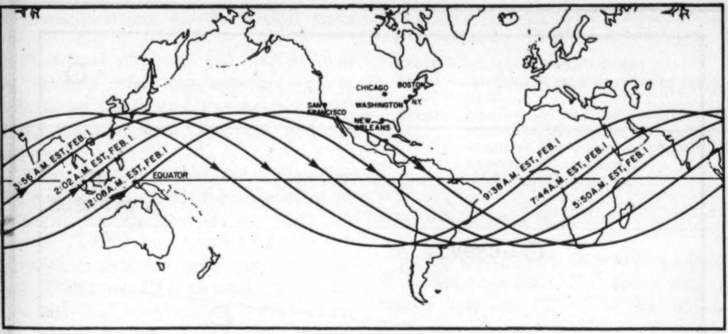


Fig. 2. *Predictions of Orbits of US Earth Satellite 1958α for the Morning of February 1, 1958. Compiled by the Naval Research Laboratory, Washington, D. C.*

The Manhattan team estimated the satellite to be as bright as a fifth-magnitude star.

Orbit: Following is the orbital information on 1958α as sent to the Special Committee for the IGY (CSAGI) of the International Council of Scientific Unions, by the USNC-IGY on February 6, 1958:

"Following orbital elements obtained by NRL from analysis 31 Minitrack observations covering first 32 revolutions 1958 Alpha. Elements include influence general perturbations and are for 0358 Zebra February one. Minimum height above earth's surface 219 statute miles maximum height 1587 statute miles period 114.95 minutes eccentricity 0.14052 inclination 33.58 degrees ascending node longitude 342.95 degrees with motion minus 4.26 degrees per day perigee argument 120.76 degrees with motion plus 6.31 degrees per day mean anomaly at epoch 14.68 degrees semimajor axis 1.2278 earth radii ascending node longitude 88 degrees 47 minutes 16 seconds East at Feb. 050647 Z, westward motion of the equatorial node is 29.13 deg. per period." (See Fig. 2.)

Phototrack

The program for volunteer photographic observations of earth satellites noted briefly in *Bulletin No. 6, December 1957*, has been formally endorsed by the USNC-IGY and is now designated program "Phototrack." Phototrack observations are expected to make a valuable supplemental contribution to the prime optical tracking network of Baker-Nunn cameras.

This program is actively supported by the Society of Photographic Scientists and Engineers (SPSE). It is designed to obtain satellite photographs meeting these specifications: Negatives are to be at least 4″ by 5″ and should be taken with a lens of at least 5″ focal length; they are to show the track of the satellite orbit against a fixed starfield background (see Fig. 3); and the trace of the satellite orbit is to contain two gaps, or displacements, timed to an accuracy of 0.1 second.

The order of accuracy of observations made to Phototrack specifications is quite high. Although the accuracy of determination of the satellite's position along its path is limited by the timing accuracy, the

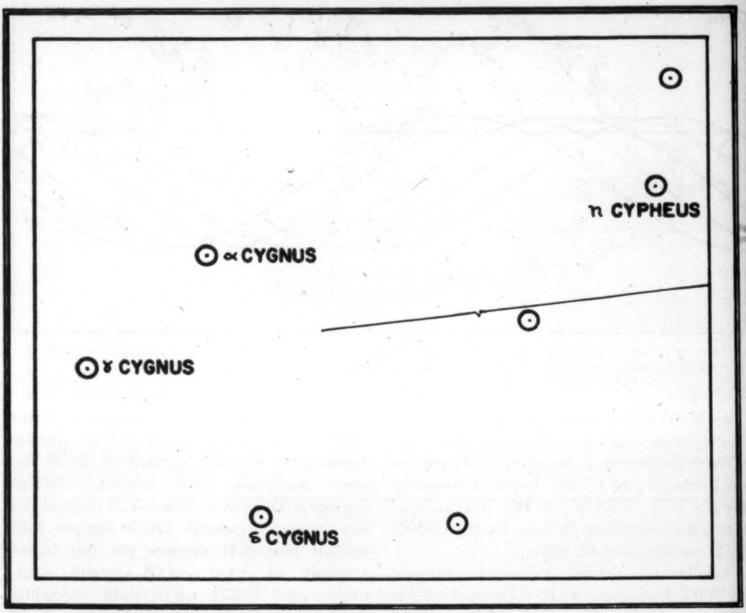


Fig. 3. *Representation of Phototrack Print Showing Track of Earth Satellite 1957β Against Fixed Starfield Background. Break in track indicates point at which camera was rapped. Taken by L. W. Tregillus, Rochester, N. Y., with a Zeiss camera having an f/6.3 Tessar lens with a focal length of 165 mm. The Kodak Royal-X emulsion was developed in DK-60 developer for 6 min at 75°F.*

position of the path itself can be determined to within 50 yards. Discrepancies of this magnitude in the satellite's predicted path can disclose information on the relative positions of the continents and on the size and shape of the earth. In addition, air drag affects the satellite's orbital period, which in turn critically affects the longitudinal changes in the satellite's apparent path over the earth. Thus, it may be possible to obtain useful air density data from measurements of the path position recorded on a Phototrack negative.

Evaluation tests are planned for improving the Phototrack technique and determining its ultimate capability.

Emulsions and Lenses

Fast emulsions must be used in Phototrack observations. Emulsions with ASA indexes of 200, developed in DK-60 for 5.5 minutes at 68°F, have recorded phototracks of 1957α1 and 1957β. These photographs were taken with lenses having apertures of less than one inch. By using the new superfast emulsions, forced development techniques, and lenses with apertures on the order of four inches, it is hoped that photographs may be obtained of objects comparable in brightness to 1957α2, which was reported to be 25 inches in diameter.

Communications for Prediction Data

Phototrack observers will need to know in advance what the optimum camera orientation will be and, in some cases, precisely when to begin, interrupt, and end exposure.

Every weekday evening since November 26, station VPZ, the Air Force station of the national headquarters of the Civil Air Patrol (CAP), has broadcast Phototrack acquisition data forecasts. These forecasts are relayed on CAP channels to the individual CAP wings and squadrons in the 48 states, District of Columbia, Hawaii, Puerto Rico, and Alaska. Should there be groups in other areas desiring to participate in the Phototrack program, efforts will be made to arrange appropriate communications through the cooperation of the IGY World Warning Agency and the cognizant IGY Participating Committee. The communications arrangements within the United States itself are presently being modified to include twilight, eclipse, and radio tracking information for satellites whose orbits are inclined at any angle to the equator. The modification will enable the CAP communications network to serve the needs of Phototrack; the visual tracking program, Moonwatch; the volunteer radio tracking program, Moonbeam; ionospheric stations; and interested newspapers within the United States.

The CAP messages will be given in the following form (The information in brackets is given only when the vertex of the track is above 40°N latitude):

On (Day) (Month) earth satellite 195- —— will be —— statute miles high and condition *(Green) (Red) (Black) (White) proceeding along curve (Inclination) (Period) [heading —— degrees across fortieth parallel] and transmitting on —— megacycles.

Vertex [fortieth parallel intercept] —— degrees west at —— Eastern Standard Time leaving condition (Black) (White) at —— degrees west at —— EST entering condition (White) (Black) at —— degrees west and —— EST.

*Black = satellite in earth's shadow.
White = satellite and satellite subpoint in sunlight.
Green = satellite in sunlight, satellite subpoint in earth's shadow (the necessary condition for visual observation of non-luminous satellites).
Red = satellite self-illuminated.

Use of Prediction Data

On any satellite pass there will be a point of nearest approach (PNA) and a time of nearest approach (TNA) to the station. Optimum camera orientation passes the camera axis through PNA, and optimum time for interruption is at TNA.

A plotting board may be prepared by placing a transparent sheet over a map or mosaic of maps showing all territory within at least 600 miles. The trace of the predicted transit can then be marked on the board with a grease pencil.

An alternative method, using a preplotted curve on a latitude-longitude grid, has been developed. Details and instructions on the use of this method are being furnished to participants in Phototrack and other volunteer observational programs.

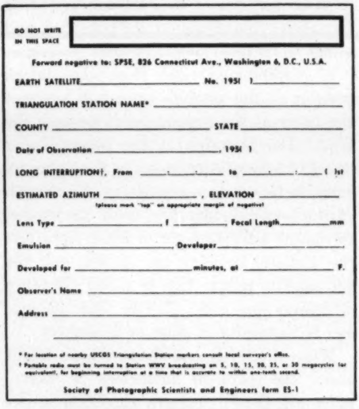
A perpendicular line from the station position to the satellite trace will intersect the latter at the ground point beneath the PNA. The direction of the perpendicular line from the station point is the optimum azimuth for camera orientation. The length of the perpendicular line from the station to the sub-satellite point at PNA represents the distance between the station and the sub-satellite point. This is called "distance of nearest approach" (DNA). This distance can be expressed in miles or in degrees.

When the DNA and the satellite's height above the earth in kilometers or statute miles are known, camera elevation in degrees above the horizon can be determined through use of tables of elevation furnished to Phototrack observers by the SPSE or by making a trigonometric calculation.

Method of Making Exposure

The Phototrack exposure should begin as the satellite enters the camera's field, be interrupted or displaced twice as it passes along the central portion, and end as it leaves. The time of nearest approach (TNA) for a properly oriented camera would correspond to the time the satellite crossed the center of the field. When the satellite is bright enough for visual observation, the beginning, interrupting, and ending of exposure can be programmed for visual control. There may be times, however, when the satellite may be bright enough to make a Phototrack record but too faint for visual control of exposure. In such cases, the TNA must be computed in advance, and a preprogrammed beginning, interrupting, and ending carried out "by the clock."

The SPSE is furnishing all participants in the Phototrack program with detailed instructions on making, timing, and identifying the photographs. Each negative taken will be filed in a jacket with a gummed label giving pertinent information on location, exposure, and development (see Fig. 4, SPSE Form ES-1).



DO NOT WRITE IN THIS SPACE

Forward negative to: SPSE, 826 Connecticut Ave., Washington 6, D.C., U.S.A.

EARTH SATELLITE ______ No. 195( ) ______

TRIANGULATION STATION NAME* ______

COUNTY ______ STATE ______

Date of Observation ______, 195( )

LONG INTERRUPTION†, From ___:___:___ to ___:___:___ ( )st

ESTIMATED AZIMUTH ______, ELEVATION ______

(please mark "top" on appropriate margin of negative)

Lens Type ______, f ______, Focal Length ______ mm

Emulsion ______, Developer ______.

Developed for ______ minutes, at ______ F.

Observer's Name ______

Address ______

* For location of nearby USCGS Triangulation Station markers consult local surveyor's office.

† Portable radio must be turned to Station WWV broadcasting on 5, 10, 15, 20, 25, or 30 megacycles (or equivalent), for beginning interruption at a time that is accurate to within one-tenth second.

Society of Photographic Scientists and Engineers form ES-1

Fig. 4. *SPSE Form ES-1. These forms are designed to accompany phototrack negatives giving pertinent information on location of observation, exposure, and development.*

To establish the time of a Phototrack observation to the required accuracy, the National Bureau of Standards' time signals, broadcast by station WWV on 5, 10, 15, 20, 25, and 30 mc, may be used.

Where the observation station is remote from standard 60-cycle power, a team of observers, using a portable receiver tuned to Station WWV can come reasonably close to the desired degree of accuracy. If one observer keeps track of time by counting time ticks, the other can drop a dark slide before the lens synchronously to a time tick and hold it there for several seconds. Positive manual cut-off with the slide is preferred to use of the shutter, which is bound to introduce time-delay uncertainties.

Where 60-cycle power is available, the SPSE recommends that an auxiliary camera be set up to photograph the time on a large synchronous electric clock. If possible the clock should be mounted in the center of a blackboard so that the date, geographical position, and other observational data can be recorded on the same negative (see Fig. 5).

The clock is photographed three times on the same negative by firing an electronic flash unit. The Phototrack camera and the flash unit are wired together in such a manner that striking a metal part of the Phototrack camera or tripod with a metal striking tool completes the circuit to fire the flash. Striking the camera also displaces the traces of the satellite and the stars on the Phototrack negative.

Prior to the predicted time of the satellite passage the clock is synchronized with WWV, working lights are turned off, the flash unit energized, and the cameras opened.

When the satellite image approaches the

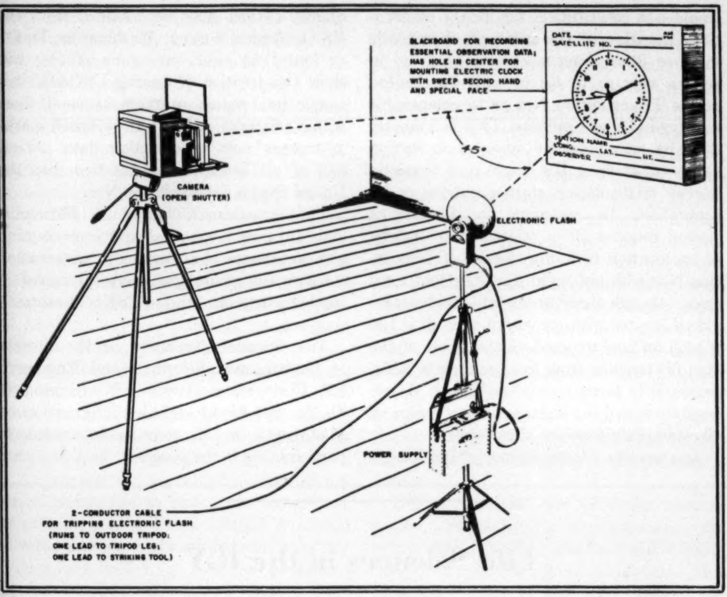

BLACKBOARD FOR RECORDING ESSENTIAL OBSERVATION DATA; HAS HOLE IN CENTER FOR MOUNTING ELECTRIC CLOCK WITH SWEEP SECOND HAND AND SPECIAL FACE
DATE
AM PM
SATELLITE NO.
12
1
3
5
6
7
9
10
11
STATION NAME
LONG.
LAT.
OBSERVER
HT.
45°
CAMERA (OPEN SHUTTER)
ELECTRONIC FLASH
POWER SUPPLY
2-CONDUCTOR CABLE FOR TRIPPING ELECTRONIC FLASH (RUNS TO OUTDOOR TRIPOD: ONE LEAD TO TRIPOD LEG; ONE LEAD TO STRIKING TOOL)

Fig. 5. *Auxiliary Camera Set Up to Photograph Precise Times of Breaks in Satellite's Track Shown on Phototrack Negatives.*

center of the field of the Phototrack camera, the observer raps the grounded part of the camera or tripod with the rapping tool, then does so again. After the Phototrack exposure is completed, the timing flash is fired again, this time synchronously with the fifth tick following the double tick of WWV.

The three superimposed images of the clock face will show three different, distinguishable times. The last recorded time, being accurately keyed to the end of the fifth second by station WWV, will permit reading-out any synchronization error so that the interruption times may be given to better than the required accuracy of 1⁄10 second.

Striking the camera or tripod during exposure will produce a displacement of the satellite image, thus sharply interrupting the streak. It is unlikely that the fixed-star traces will settle down to where they left off before the tap, or that the satellite streak will continue in precisely the same line. The result will be three segments of satellite streak related to three mutually displaced sets of star traces. The shortest (middle) streak, however, can readily be related with precision to the faintest (and shortest) set of star traces. The means employed for producing the discontinuities and for recording their times are positive, do not require calibration, and supply the data in a self-evident form.

Location of Phototrack Station

By itself, a perfect Phototrack negative, together with its chronograph negative, would not constitute a significant observation. Location of the point of observation in three dimensions must also be given in such a way as to tie in with the United States Triangulation Net or to comparable surveys in other countries. This is normally done by surveying the observation station as an offset to a US Coast and Geodetic Survey triangulation station marker or its equivalent. In summary, a Phototrack station requires (1) a "closed loop" survey of its location tied into the US Triangulation Net with not more than one foot total error—though observations will still be valuable if located with errors not exceeding 100 ft.; (2) an unobstructed view of most of the sky; (3) freedom from local sources of light, particularly passing auto headlights; (4) accessibility; and (5) location near a source of 60-cycle electric power, if possible.

Appropriate topographic "Quadrangle Sheets," which may be obtained from the US Geological Survey, Washington, D. C., or found in most surveyor's offices, will show the location of nearby USC&GS triangulation station markers as small dots within triangles, and of nearby bench marks as crosses next to elevation data. About half of all bench marks are tied into the United States Triangulation Net.

The American Congress on Surveying and Mapping is encouraging its members to give assistance in surveying-in observation stations for groups genuinely interested in participating in the SPSE Phototrack program.

The Secretary-Treasurer of the Society of Photographic Scientists and Engineers, 826 Connecticut Avenue, Washington 6, D. C., will furnish detailed information on Phototrack to all persons interested in participating in the program.

Life Sciences in the IGY

While the International Geophysical Year is by definition concerned with studies in the physical sciences, the USNC-IGY has recognized that its program includes activities in relatively inaccessible regions. Therefore, research workers in the life sciences have been encouraged to take advantage of the unique opportunities provided by the IGY program and to use IGY facilities for work in their own disciplines.

Marine biology studies are conducted on all IGY oceanographic cruises (for examples of the type of work done, see the report of the "Cruise of the Brown Bear" in this issue.) Investigations in dentistry, human and animal physiology, psychology, botany, and animal migration are being conducted at US-IGY Antarctic Stations. At US-IGY Arctic Drifting Stations A and B, continuing investigations in marine biology, with particular reference to microorganisms and nutrition supply, are carried on. Even the earth satellites will be used for basic biological research. It is planned to place small living organisms, in the form of yeast, in one or more of the test spheres launched in the Vanguard program.

Brief outlines of the main problems being studied at Antarctic and Arctic IGY stations and the methods of attack on these problems are given below.

Antarctic

Dentistry: Experience on past polar expeditions indicates that dental disorders are among the most troublesome problems encountered in extreme cold. The most usual malady encountered is toothache. All devitalized and carious teeth become painful, often requiring extraction. When cold air is brought in contact with diseased teeth, the pain is often considerable. As the cold increases, alloy fillings appear to contract and pull away from the cavities they protect. Some fall out, while others leak, resulting in decay beneath the fillings. Front teeth, particularly those having large fillings and gold inlays, become quite painful on exposure to low temperatures. These difficulties have been encountered in the US-IGY Antarctic program despite attempts to prevent them by examination and treatment prior to departure from the United States.

In view of these cold-weather dental problems, the Committee on Dentistry of the National Academy of Sciences, Division of Medical Science, suggested that dental research during the IGY should be considered. The US Navy's Bureau of Medicine and Surgery has requested Navy dentists stationed at Little America and McMurdo Sound to undertake such investigations as time and facilities permit.

Among the factors being investigated are those giving rise to pain under conditions of extreme cold and their relation to dental effects. Various types of material used for fillings are tested, as well as protective devices such as rubber teeth guards worn by athletes. Temperature changes in the mouth are being measured under a variety of conditions. The relationship of dental complaints to psychosomatic factors (e.g., stress and incidence of medical complaints) is being studied.

Human Physiology: The human physiology program emphasizes the unique conditions confronting US-IGY Antarctic personnel with regard to climate, length of stay, and related factors. The degree of cold exposure is likely to be more severe than anywhere else in the world. The duration of stay is sufficiently long to uncover major trends in physiological readjustment, if such occur. The location of stations, from sea level to an altitude of about 9,200 feet, offers an opportunity to compare the effect of cold by itself with cold plus altitude on man's ability to adapt to his environment.

Work on these questions is being conducted at the Little America Station by a physiologist from the US Air Force Arctic Aeromedical Laboratory, Fairbanks, Alaska. The medical doctor at this station is assisting in the program. At each of the other US-IGY Antarctic stations the station medical doctor is carrying out basic physiological measurements.

Physiological measurements include changes in thickness of body fat, heat production, mobility of joints, and touch discrimination. Measurements are being made on personnel whose duties involve a maximum of out-of-door work, as well as others whose duties require a minimum of outside work. These measurements will be compared. Important correlative data are being obtained by various tests on physical fitness and on increase or decrease in cold injury and its relationship to these measurements.

During the 1957–58 Antarctic summer period, physiological investigations are being carried out by Nello Pace and William Siri of the University of California. This program is part of the joint British and United States Medical—Physiological Expedition and is under the auspices of the U. S. Office of Naval Research and the British Medical Research Council. Particular attention is being paid to the various traverse parties.

Psychology: It is clear from studies of situations involving stress, isolation, and deprivation that individuals respond very differently to such situations. Definitive data for the indoctrination of men going into such situations are lacking. The psychological research program has as its aim the collection of historical data of reasonably intimate personal significance by two methods: written diaries and voice recordings. These data are being collected from personnel at the IGY Amundsen-Scott South Pole, Byrd, Wilkes, and Ellsworth IGY stations.

The Program is under the direction of the

Division of Neuropsychiatry, Walter Reed Army Medical Center, and the Navy Bureau of Medicine and Surgery. Diaries have been given to personnel at these stations and they have been requested to record difficulties in adjustment to weather, limited space, and chores, as well as methods found useful for improving the situation or facilitating adjustment. Attitudes toward problems in the use of equipment and toward work progress, relations to, and importance of, radio communications with other bases and with home, and the kinds of news that seem important, are also being noted.

Development and changes in sub-group relationships, changes in informal organization of the station group, major topics of conversation, incidents of irritability and their management, complaints, distribution of activity, and attitudes toward the sense of passage of time are also being recorded by personnel, both in diary form and on records.

Subsequent analysis of these data by the Division of Neuropsychiatry, Walter Reed Army Medical Center, and the Navy Bureau of Medicine and Surgery will, it is hoped, provide a clearer picture of individual reactions and of group relations under conditions of isolation and stress.

Botany: George A. Llano, Arctic Institute of North America, is making a study of the relationship of the present vegetation of the Antarctic, specifically the lichens, to ice and snow terrain and to fluctuations in the extent of glaciation. He has made collections at McMurdo Sound, Hallet Station, and Wilkes Station.

Animal Physiology: Frozen whole specimens of Adelie and Emperor penguins are being returned from Wilkes Station for study of the anatomy of their respiratory systems.

A telemetering device is in use at Wilkes Station which, when placed inside the egg of a penguin, skua, or other bird, broadcasts the temperature to a recording mechanism. This program is under the direction of Carl Eklund, Wilkes Station Scientific Leader, and will be continued by Willis Tressler, his relief.

Animal Migration Studies: This program was initiated by Carl Eklund at Wilkes Station and will be continued throughout the coming season.

The migration and distribution of the Antarctic skua is under investigation by means of colored plastic bands attached to the legs of these birds. Personnel manning stations of other countries participating in the IGY Antarctic program have been supplied with bands of a distinctive color, so that subsequent observations will give information on the points of origin of banded birds.

Seals are being marked at Wilkes Station by means of a branding iron bearing the initials IGY. Personnel at coastal stations have been alerted to record the appearance of these seals.

Arctic

Sea Ice Studies: It is planned to study the physiology of frozen organisms, including cytological studies of organisms that survive seasonal freezing in sea ice, to determine the mechanisms which enable such organisms—diatoms, protozoans, and higher forms—to survive. In relation to this study, gas diffusion through sea ice, using the Scholander and Evans method and with emphasis upon CO_2, N_2, and O_2, will be investigated.

The solubility of nutrients in sea ice, e.g., O_2, CO_2, PO_2, NO_2, and NO_3, will be studied, as well as the activity of bacteria in sea ice, mechanical effects of freezing on organisms, and respiratory exchanges of frozen organisms.

Marine Biology: At drifting stations A and B the program in marine biology will include periodic sampling and preservation and examination of phytoplankton, zooplankton, and allied life forms.

Cruise of the Brown Bear

This report is based on material furnished by Robert G. Paquette, Department of Oceanography, University of Washington.

The study of the deep currents of the oceans is one of the primary objectives of the IGY oceanographic program. Little is known about the circulation of the deep waters, yet a knowledge of the heat exchange involved in the movement of water between low and high latitudes may be of great importance in long-range weather forecasting. Also, the rate of exchange of mineral-rich deep water with surface water determines the fertility of the oceans and sets a limit on the amount of food man can take from them.

As part of the IGY study of the deep waters, scientists aboard the oceanographic vessel *Brown Bear*, of the University of Washington, conducted investigations during July, August, and September 1957 in the Aleutian Trench, the Aleutian passes, the Bering Sea adjacent to the Aleutian Islands, and parts of the Northeast Pacific. Thirty-six oceanographic stations were occupied during the cruise.

Four of the stations were reoccupations of stations made by the non-magnetic ship *Carnegie* in 1929. In 1958, the *Brown Bear* will reoccupy seven of the *Carnegie* stations, thus making possible studies of changes in the observed phenomena in time as well as in space. Fig. 6 shows the route of the *Brown Bear* in 1957 and the stations occupied, the cruise proposed for the *Brown Bear* in 1958, and the stations occupied by the *Carnegie* on its cruise VII, 1929.

The major IGY objective of the 1957 cruise was to gather data for a north-south profile of water properties extending from the surface to or near the bottom. On most stations, chemical and temperature measurements were taken from the surface to the bottom. Eleven samples were taken from deep and surface waters for dating by the carbon-14 method. A second major objective was a preliminary survey of the circulation of water through the Aleutian

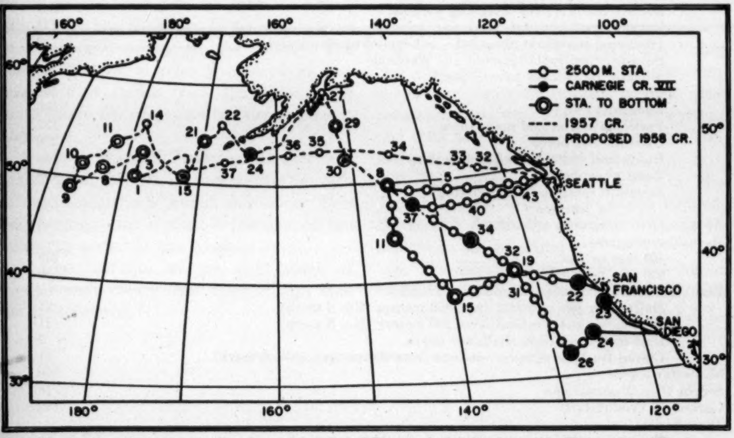


Fig. 6. *Chart Showing the Tracks of the 1957 and Proposed 1958 Cruises of the University of Washington Oceanographic Vessel* Brown Bear. *Black dots represent stations occupied by the nonmagnetic ship* Carnegie, *in 1929.*

passes as observed by a series of station sections through the passes.

Other objectives included:

1. Dating of the deep water by C^{14} methods.

2. A program of special chemistry including determination of silicate, pH, alkalinity, total phosphorus, particulate iron, manganese, calcium, and boron.

3. Routine productivity determinations by C^{14} methods, both underway and on station.

4. Direct measurement of currents north of Kodiak Island—in Shelikof Strait and on the shelf to the south. Both sets of observations were to continue for 29 hours to obtain an indication of the net current flows in these regions, which cannot be studied by the usual dynamic methods. Net flows in these areas may be important in the water-transport budget of the Gulf of Alaska.

Routine observations included salinity; temperature; oxygen; dissolved inorganic phosphate; bathythermograms and associated weather data; bathymetry; and a few bottom cores. A numerical summary of the observations made on the cruise is given in Table 1.

Although biology is not one of the primary IGY disciplines, most IGY oceanographic vessels conduct biological investigations. The *Brown Bear* made a total of 149 hauls with a 6-foot Isaacs-Kidd midwater trawl at depths ranging from about 20 to 275 meters. The hauls were made, weather permitting, along the regular cruise track. A fair number of species of rare, deep water fish were taken. A note-

Table 1. *Numerical Summary*

		Number:
Stations Occupied:		
6000–7280 meters		5
4000–6000 meters		1
2000–4000 meters		6
0–2000 meters		24
Chemical Samples Taken:		
Salinity 742 + 165 (time series)		907
Surface salinity, not including stations		367
Oxygen		731
Dissolved inorganic phosphate, not including duplicates		734
Silicate, spectrophotometric (El Wardani)		500
Silicate, by Nessler tubes (Gast)		144
pH		506
Alkalinity		506
Particulate iron and manganese		137
Calcium and boron		216
Boron and iodine (Gast and Barkley)		144
Total phosphorus	approx.	200
50-gallon samples for age-dating:		
a. surface		6
b. deep		5
Bathythermograms:		
450 feet or less		248
900 feet nominal		189
Plankton Hauls (exclusive of midwater trawls):		
Half-meter net, vertical from 400 meters (No. 6 mesh)		21
Half-meter net, vertical from 200 meters (No. 6 mesh)		21
Half-meter net from shallower depth		2
Clarke-Bumpus sampler, oblique from 200 meters, (No. 6 mesh)		21
Midwater trawls		149
Secchi Disc Observations		16
Carbon-14 Productivity		110
Time Series:		
Currents, salinity, temperature, bathythermograms		2 × 30-hrs.
Individual Current Measurements		228
Bottom Cores with 2-Foot Gravity Corer		6

worthy catch was two eel larvae still in the leptocephalus stage. At the time of capture they were alive and, except for their eyes, transparent. This may have been the first capture of this animal in the area.

Wildlife observations were made continuously and the scientific watch made an entry on a special wildlife-observations form once during each watch. These observations were supplemented by observations of the pilot house watch and by nightlight studies carried out on station when sea conditions permitted. Wildlife observed included whales, porpoises, seals, birds, surface fish, and floating organisms.

Hydrographic observations in the physical oceanographic program were analyzed and the results entered on punch cards while still at sea, thus making the data available for further analysis by machine methods soon after the ship's return to port.

Preliminary results of the program as deduced from the data at this state are:

1. The Aleutian passes are regions of high currents, where powerful upwelling and mixing processes are evident on the bathythermograms to depths as great as about 275 m. Abrupt decreases in temperature as great as 10°F appear at the surface. The modified water is readily evident at distances of 30 miles from the passes, and more subtle effects probably exist at greater distances.

2. Along Shelikof Strait, a net flow was found at all depths, setting southwest with average magnitude about 0.5 knot. This may account for a sizable fraction of the inflowing water in the Alaskan gyral.

3. The currents on the shelf south of Kodiak were rotary. Net flows, if any, were not well defined.

4. Below 2000 m the waters of the Aleutian Trench are very nearly the same throughout. One exception was noted, however: the oxygen concentration at Station 10, at the extreme westerly end of the track, is lower by about 0.015 milligram-atom per liter than at Station 15, in the central portion. Correspondingly, the temperature at the western end is higher by 0.02° to 0.10°C. Temperature increases by 0.05° to 0.20°C and oxygen decreases by 0.03 to 0.05 milligram-atom per liter along the clockwise arc from Station 15 to Station 31. Station 8 is anomalous in having the highest oxygen concentration of all stations in the Trench. Below 6000 m the temperature profiles at the several stations in the Trench are not significantly different. In contrast to the temperatures, the differences in oxygen concentration are maintained all the way to the bottom.

5. In the Trench, the oxygen concentration reaches a maximum of about 0.33 to 0.35 milligram-atom per liter at about 6000 m. It then decreases about 0.025 milligram-atom per liter towards the bottom. This latter effect may be caused by reaction of the oxygen with the metal of the bottles during the long hauling period.

6. The three deeper stations in the Bering Sea (Stations 3, 11, and 21) were very similar in temperature and oxygen concentration, and were 0.08° to 0.12°C warmer and 0.05 to 0.08 milligram-atoms per liter less concentrated than Station 15.

7. The minimum temperature in the Trench is 1.44° to 1.47°C at about 4000 m. Below this depth the gradient with depth is close to the adiabatic.

8. The salinity below 6000 m was found to be lowest at Station 15, 34.691 %, and greatest at Station 10, 34.698 to 34.706 %.

The Microbarovariograph: A New Instrument For Measuring Minute Atmospheric Pressure Variations

The following material was supplied by William L. Donn, Lamont Geological Observatory.

Studies of the interactions between the atmosphere and hydrosphere are essential to an increased understanding of the earth's heat and water budget. Such studies are, therefore, an integral part of the IGY program. (See *Bulletin No. 2, August 1957.*) In order to facilitate investigation of these interrelationships, instrumentation producing data which can be readily coupled with data obtained for related studies in the allied discipline are sought by both meteorologists and oceanographers.

Meteorologists have long felt a need for a simple, compact ultra-sensitive barograph that would respond to small changes of pressure over any given range. Such an instrument, the microbarovariograph, has been developed by the Lamont Geological Observatory of Columbia University for use in the IGY island observatory program. The instruments will be located near long-period ocean wave recorders in order to study the effects of air-to-water energy coupling.

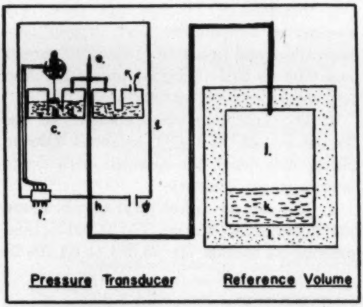


Fig. 7. *Schematic Diagram of Microbarovariograph Transducer. Legend: a. electromagnetic pickup; b. cork float; c. compliance chamber; d. Di-octal Sebacate; e. slow leak; f. metal cover; g. fast leak; h. plastic tubing; i. electrical connector; j. reference volume; k. calcium chloride solution; l. thermal insulation.*

Basically, the microbarovariograph pressure unit is designed to study: (1) propagation of internal waves in the atmosphere, and (2) the phenomena of wave coupling between the atmosphere and oceans.

The passage of internal waves along an atmospheric discontinuity aloft produces surface perturbations in pressure and wind. The wind effect is difficult to isolate if the ambient wind is strong, but the pressure variations can be recorded easily by the microbarovariograph, permitting study of the velocity and propagation direction of the waves aloft. Moreover, under the proper conditions, violent natural and artificial disturbances can be detected by an array of these instruments at a great distance from the event. Such information is of great value in understanding the dynamic structure of the atmosphere.

Strong marine or lake storm surges have occurred from the effects of coupling to corresponding surges (often waves) in the air. These severe disturbances can usually be detected by conventional instruments

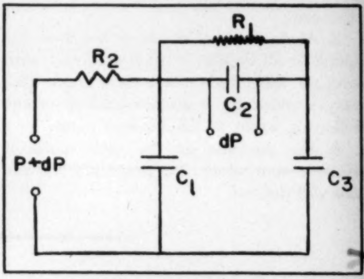


Fig. 8. *Electrical Analog. Legend: R_1. fast leak (short-period response); R_2. slow leak (long-period response); C_1. compliance chamber; C_2. compliance of liquid; C_3. compliance of reference volume; P. ambient atmospheric pressure; dP signal pressure.*

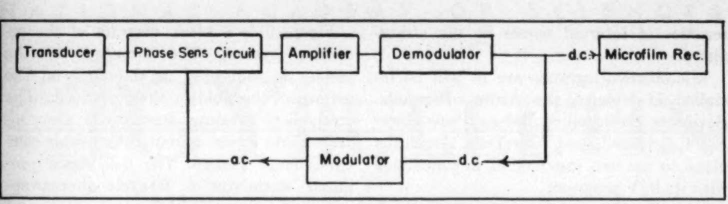


Fig. 9. *Block Diagram of Microbarovariograph Recording System.*

but are too infrequent to provide adequate data for complete study. The sensitive microbarovariograph used in conjunction with a long-period wave recorder permits study of less pronounced but scientifically important cases of coupling. From these a better understanding of the energy transfer between sea and air can be gained.

The instrument is also excellent for the study of short-period turbulence in the air; its response shows every gust of wind. It also shows long-period pressure variations and, owing to its ability to record thermal effects, on clear days it can be used to mark the approximate times of sunrise and sunset.

A record of small amplitude, long-period pressure changes will be of particular value in the study of tsunami waves (so-called tidal waves produced by submarine earthquakes, landslides, or volcanic action) since it is expected that pressure oscillations in the atmosphere will affect the long-period wave record. In tsunami studies, the atmospheric pressure record will be applied as a correction to the water pressure record. Widespread use of the instrument in the Atlantic will also aid in gathering data for a closer study of the propagation charac-

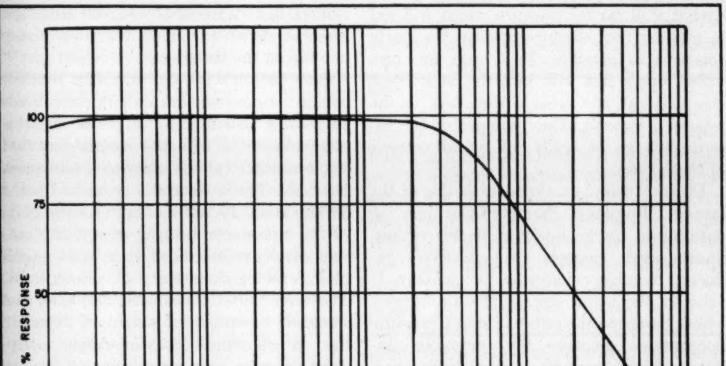


Fig. 10. *Typical Response Curve of Microbarovariograph Transducer.*

teristics of internal waves in the atmosphere.

Microbarovariographs are or will be installed in Iceland, the Azores, Bermuda, Barbados, Ascension, St. Helena, Texas Tower No. 4, and Fire Island, New York. Argentina plans to use two instruments in connection with its IGY program.

The microbarovariograph is a rate-of-change pressure recorder, utilizing a pressure transducer developed by Wallace of Wallace and Tiernan, Inc. The pressure transducer is essentially a U-tube manometer (see Fig. 7) open at one end to the dynamic pressure fluctuations of the atmosphere and at the other to a thermally insulated chamber maintaining a relatively constant temperature. The fluid used in the transducer is Di-Octal Sebacate, a commercial plasticizer, selected especially because of its small temperature coefficient of expansion and low volatility and creep. A saturated solution of calcium chloride is used to adjust the reference volume to a pre-determined value and to maintain within it a partial pressure which will aid in keeping the reference pressure as nearly constant as possible. Two leaks are provided, one a fast leak into the compliance chamber and the other a slow leak in the reference volume. The response of the instrument can be easily set by adjustment of these leaks.

Figure 8 shows an electrical analog of the system. Response characteristics can be determined by an analysis of this circuit. Short-period changes are effectively reduced by the connection of another U tube in the same line as the transducer, which dampens the effect of quick pressure fluctuations. Because the thermally-insulated reference volume is large in comparison to the pickup volume in the manometer, the temperature drift is negligible.

Figure 9 is a block diagram of the recording system. The armature of the pickup is connected to the float on the surface of the fluid in the transducer. The mechanical pressure fluctuations are converted into direct current by a simple electro-dynamic pickup. The d.c. signal produced modulates a 60-cycle alternating-current carrier. Following two stages of amplification, a demodulator converts the output signal to d.c., which drives a Lamont microfilm recorder. The feed-back circuit utilizes a magnetic modulator to return the d.c. output signal to a.c. The maximum resolution possible is about .002 mb. The approximate dynamic pressure range is 0.12 mb. The operating sensitivity used depends upon the resolution and the response desired, with the limitation that the slow leak must be capable of effectively eliminating all large diurnal pressure changes.

Figure 10 is a typical response curve of the transducer. Reference to the curve shows that it is relatively flat between 10 secs and approximately 200 secs. It reaches half value at about 2000 secs. The response curve was computed from a step impulse on the transducer.

Once set up with the microfilm recorder loaded, the instrument can operate unattended for one month. A panel meter is placed in series with the recorder so that the operation can be checked at frequent intervals. The instrument operates from a 50–60-cycle, 110-volt a.c. line. All the parts of the transducer housing except the outside cover are machined from plastic, and plastic tubing connects the various units. The three units (transducer, amplifier, and recorder) have a total weight of about 12 lbs. A standard Esterline-Angus strip-chart recorder may be substituted for the Lamont microfilm recorder by using alternate output plugs on the amplifier.

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IGY BULLETIN

A monthly survey by the U. S. National Committee for the International Geophysical Year. Established by and part of the National Academy of Sciences, the Committee is responsible for the U. S. International Geophysical Year program in which several hundred American scientists are participating and many public and private institutions are cooperating.

IGY Antarctic Oversnow Traverses

Although 11 nations have established 38 new scientific stations in the Antarctic for the IGY, observations made at these widely-distributed stations can furnish only a portion of the geophysical data needed for a complete understanding of this 6,000,000-square-mile region of ice and rock. To fill some of the major gaps, a series of oversnow scientific traverses were organized as part of the US-IGY Antarctic Program for the summer seasons of 1957–58 and 1958–59.

Three major oversnow traverses scheduled for the 1957–58 summer season by the US-IGY have been completed—the Ross Ice Shelf traverse from IGY Little America Station; a traverse of parts of Marie Byrd Land and the Ellsworth Highland from IGY Byrd Station; and a traverse across the Filchner Ice Shelf and parts of Edith Ronne Land from IGY Ellsworth Station (see Fig. 1). They were preceded in January and February 1957 by a tractor-train traverse from Little America to Byrd Station, 647 mi eastward over the ice cap. Glaciologic and seismologic measurements were made on this first traverse; experimental and logistic procedures and techniques were tested and perfected. A full four months of field work is planned for each of the summer seasons, which begin in October and end in March, despite an interruption about mid-season for the annual replacement of personnel.

Scientific Objectives

In the traverse program seismic techniques are used to measure the thickness of the ice and to determine the character of the subglacial floor and of exposed land areas. Ground control, for subsequent survey operations, is established wherever rock outcrops occur. Core, pit, and surface studies are made to provide data on snow stratigraphy and on the movement, volume, thermal and hydrologic regimen, recent mass changes, and crystallography of the ice.

Gravity measurements, partly in association with the seismic work, and measurements of the earth's magnetic field strength and of magnetic compass variations are included in the basic traverse programs. Standard meteorological information is obtained on all traverses for transmittal to the IGY Antarctic Weather Central at Little America Station. (*Bulletin No. 4, October 1957*, contains a detailed report on the Weather Central.) Airborne seismic and glaciological traverses, to make spot measurements in areas inaccessible to surface parties, are also part of the program.

Although geologic study reveals that the Antarctic ice mantle was once about 1000 ft thicker than it is now, it is not yet known whether the total ice mass is at present increasing or decreasing. Some estimates suggest that it may be in a state of approximate equilibrium, but a large

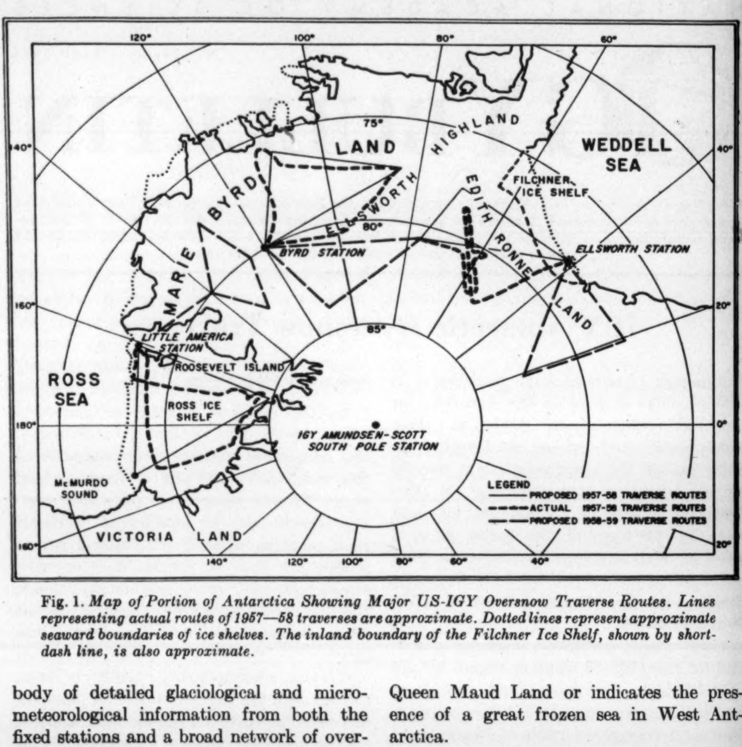
120°
100°
80°
60°
75°
BYRD LAND
ELLSWORTH HIGHLAND
WEDDELL SEA
140°
40°
FILCHNER ICE SHELF
EDITH RONNE LAND
80°
BYRD STATION
ELLSWORTH STATION
MARIE
160°
20°
85°
LITTLE AMERICA STATION
ROOSEVELT ISLAND
ROSS SEA
ROSS ICE SHELF
180°
0°
IGY AMUNDSEN-SCOTT SOUTH POLE STATION
McMURDO SOUND
LEGEND
PROPOSED 1957-58 TRAVERSE ROUTES
ACTUAL 1957-58 TRAVERSE ROUTES
PROPOSED 1958-59 TRAVERSE ROUTES
VICTORIA LAND
160°
20°
140°
120°
100°
80°
60°
40°

Fig. 1. *Map of Portion of Antarctica Showing Major US-IGY Oversnow Traverse Routes. Lines representing actual routes of 1957—58 traverses are approximate. Dotted lines represent approximate seaward boundaries of ice shelves. The inland boundary of the Filchner Ice Shelf, shown by short-dash line, is also approximate.*

body of detailed glaciological and micrometeorological information from both the fixed stations and a broad network of oversnow and airborne traverses must be accumulated and analyzed before final conclusions can be reached.

The early traverse from IGY Little America Station to Byrd Station resulted in the first extensive evidence that the Antarctic continent is overlaid with a far greater volume of ice than long thought. (Byrd Station, about 5000 ft above sea level, rests on about 10,000 ft of ice.)

Gravity and seismologic data obtained on these traverses may show whether the sub-sea-level portion of the ice sheet, such as exists beneath Byrd Station, occurs in fjord-like depressions similar to those found to exist under the Greenland ice cap and Queen Maud Land or indicates the presence of a great frozen sea in West Antarctica.

Data acquired on the traverses will also contribute to knowledge of the relationships between Antarctic ice and the supply and movement of cold ocean waters, as well as between the ice and Southern Hemisphere weather and climate.

1957–58 Traverses

IGY Little America Station—The traverse party from Little America had as its objective during the past season the study of the mass and volume, thickness, hydrologic economy, morphology, and structure of the Ross Ice Shelf. The depth to the sea bottom beneath the floating ice shelf was measured by seismic methods, investigations were made of mountain ranges and peaks along the edge of the shelf, and wind-drift—or sastrugi—patterns were studied.

The Ross Ice Shelf extends more than 400 mi into the Ross Sea embayment from a point about 300 mi from the South Pole. Its maximum width is approximately 500 mi and its area about 160,000 square mi. Recent seismic studies by IGY scientists at Little America Station made in the vicinity of the station but away from the edge of the shelf, show an ice thickness ranging from nearly 790 to about 1050 ft. The ocean bottom was shown to be about 2070 to 2155 ft below the ice surface, indicating that this part of the shelf floats on well over 1000 ft of water.

Gravity measurements made this summer at IGY Little America Station indicate vertical movement of the shelf of several feet. Motion is very small 7 mi from the station and entirely absent at distances of 20 to 30 mi. It has been estimated that the shelf moves seaward at the rate of about 5 ft/day. The additional seismic and gravity measurements accumulated on the Ross Ice Shelf traverse will ultimately permit a more complete synthesis of the physical character of the entire shelf.

It is apparent from ice-fracture patterns that the Ice Shelf is grounded in many places. Although the islands on which it is grounded do not generally penetrate the ice, they may be identified by hinge cracks, higher elevations, and ice-fracture patterns. These features were mapped wherever possible along the traverse route.

Initial plans for the Ross Ice Shelf traverse prescribed a triangular route from Little America Station westward to McMurdo Sound, southeast to the Beardmore and Liv Glaciers at the southern edge of the shelf, and northeastward back to Little America Station (see Fig. 1). This route was generally adhered to, although McMurdo Sound was by-passed to maintain the planned time schedule, and several deviations were made for special studies.

The traverse party, consisting of eight men led by Albert P. Crary, Station Scientific Leader at Little America and Deputy Chief Scientist for the USNC-IGY Antarctic Program, left its home station on October 24, 1957.

Reports issued while the traverse was in progress listed, through January 1958, a total of 34 seismic, 179 gravity, and 160 magnetic stations occupied; 26 glaciological pit studies made; 130 ramsonde measurements taken (the ramsonde, or ram penetrometer, is an instrument for determining physical properties of the snow by recording the amount of force required to drive a rod a given distance into it); and weather observations made at 281 stations. In addition, ice temperature and density were measured at a depth of about 30 ft in 31 drill holes, 55 ft in one drill hole, and 65 ft in three drill holes.

R. L. Viets, geomagnetician at Little America Station, visited the traverse party briefly at 82°S, 170°E, where he was able to make successful magnetic field observations with a magnetometer provided by New Zealand IGY scientists.

Elevation of the ice surface was measured continuously along the traverse route by the "altimetry leap-frog method," which employs three crews to make successive atmospheric pressure measurements at each site. Sites occupied are five miles apart. This method provides enough data for each position to permit corrections for fluctuations in atmospheric pressure, allowing much more accurate altitude determinations than would be possible with single observations.

Employing this technique, the Ross Ice Shelf traverse party found that the shelf's elevation varies overall by about 60 ft. In general, however, the Ice Shelf appeared virtually featureless. Only two small islands, situated just west of Roosevelt Island, and two small depressions broke the evenness of the ice surface during the first leg of the route.

The traverse party returned to IGY

Table 1. *Seismic Data Obtained on Byrd Traverse 1957—58*

Lat. (S)	Long. (W)	Elev. above sea level (ft)	Ice Thickness (ft)	Remarks
79°11′	116°36′	5625	7955	Southwest border of hilly region
78°44′	114°57′	5935	6890	Maximum surface elevation
78°30′	114°50′	5775	5165	Point of minimum ice thickness; highest point of rock floor in 20 mile zone; only area with rock floor above sea level
77°54′	113°16′	4980	8200	Basin area
77°28′	112°22′	4625	6990	Second hilly region
76°48′	112°50′	4215	9285	Basin adjoining mountain
76°19′	111°46′	4920	0	Exposed rock on mountain
76°58′	109°07′	3900	7695	Represents 100-mile, flat surface and ice bottom east of mountain
77°27′6″	100°26′	4625	10,825	Maximum ice thickness

Little America Station on February 13, 1958, after 113 days in the field. The overall length of the traverse was 1450 mi.

IGY Byrd Station—The broad objective of the Byrd Station traverse for the 1957–58 summer season was to determine the general nature of the ice sheet and of protruding mountains in eastern Marie Byrd Land and in the Ellsworth Highland to the east of Byrd Station. Although specific types of measurements were similar to those made on the Ross Ice Shelf traverse, the existence of thousands of feet of inland ice resting on a bedrock surface in the region covered by the Byrd party constituted a major environmental difference.

The Byrd Station traverse party, led by Vernon Anderson, IGY glaciologist, departed on November 19, 1957. Radio schedules were arranged with the Ellsworth traverse group for exchange of information.

Excellent seismic reflection data were obtained throughout the traverse. Table 1 gives ice thicknesses and elevations of the surface at representative points along the first and second legs of the traverse; at only one of these locations does the subglacial floor rise above sea level, and at the last location the ice thickness, surface elevation, and bedrock depth are similar to those at Byrd Station. At distances of 100–200 mi west of the Sentinel Mountains, the apex of the second and third legs of the traverse, ice thicknesses were generally more than 10,000 ft; the maximum measured was 11,610 ft. The seismic records for most of the traverse route indicate rugged, variable topography characterizing a subglacial floor almost everywhere below sea level.

The Byrd Station traverse party collected samples of volcanic rocks and lichens in the region of an unnamed mountain range about 250 mi northeast of Byrd Station. One unusual biological observation was the discovery of penguin tracks along the traverse route at a point more than 150 mi from the nearest known coast.

Although figures for the entire traverse are not yet available, an idea of the party's experimental activities may be formed from the following list compiled for the month of December, 1957. During that period, the traverse party made 13 short refraction profiles, 110 gravity and magnetic readings, 12 glaciological pit studies, and 55 intermediate-depth ramsonde measurements. Six days were spent at the Sentinel Mountains making long seismic-refraction profile studies and collecting rock samples. After leaving the Sentinels, increasing surface noise interfered with seismic work.

At the Sentinels, study of a nunatak (isolated peak or hill projecting through a glacial surface) indicated a former ice level 800 ft above the present surface. Investigations were made and rock samples collected at five nunataks. Glaciological studies along the traverse route showed an accumulation of about 20–30 inches of snow during the past year.

The traverse ended on February 23, 1958, with the return of the party to IGY Byrd Station after 96 days in the field and a trek of about 1200 mi.

IGY Ellsworth Station—The Ellsworth Station traverse investigated the Filchner Ice Shelf and the inland ice of Edith Ronne Land, combining the types of measurements made by both the Little America and Byrd traverses. An important goal of this traverse was to occupy a point that could also be reached by next summer season's Byrd Station traverse, thus providing a link for the correlation of data.

The traverse party left IGY Ellsworth Station on October 28, 1957, led by Edward C. Thiel, glaciologist. The party had been held up several days while airborne efforts were made to find a safe passage through a heavily crevassed area in the first 50 miles south of Ellsworth Station. A crevasse-free passage towards the east and with elevations of 700 to 3000 ft above sea level was found.

The party deviated about 120 mi from the planned route to make geological studies and collect rock specimens at a newly reported mountain range. The range, estimated to be 11,000 ft high in places, is reported to be about 400 mi from the South Pole, trending east-west throughout its length of about 100 mi. It was discovered from the air by Finn Ronne, then scientific leader at IGY Ellsworth Station.

On December 22, another mountain range, first sighted on a reconnaissance flight early in 1957, was reached. These mountains have an average height of 6500 ft and extend east-west along 82°33′S for about 30 mi, between 51° and 55°W. Black bands were noted high on the mountains, and a 5000-ft escarpment was discovered on the southern side.

A 3200-ft, ice-covered island extending for about 230 mi south and west from Gould Bay was observed for the first time. Seismic soundings showed the land surface beneath the island's ice mantle to be hundreds of feet above sea level. Other islands, whose contours were not fully delineated, were seen still farther westward. They appear to tie in with land in the Sweeney and Lowell Thomas Mountains at the western end of the Filchner Ice Shelf.

The traverse party encountered several crevasse fields along the route. In early January 1958, after reaching a difficult crevasse field at 78°40′S, 69°W, about 80 mi from Mt. Hassage, at the apex of the second and third legs of the traverse, the party was evacuated by air. A relief party had been flown in to attempt to continue the traverse. To that point, the traverse had covered 816 mi, including a large portion of the Filchner Ice Shelf and considerable inland stretches. The relief party backtracked in an effort to find an open route to Ellsworth Station. It then turned southward to the midpoint station, where the vehicles and equipment were cached for use by next year's party.

Other traverses: 1957–58—Personnel remaining at US-IGY Antarctic stations conducted several short traverses in the vicinities of their stations during the 1957–58 Antarctic summer season. The aims were basically similar to those of the major traverses.

The airborne seismologic traverse program was inaugurated with flights into Victoria Land, on the ice cap east of McMurdo Sound. Original plans scheduled landings at 50-mile intervals. Between January 2 and 22, 1958, three stations were occupied for the purpose of making glaciological, gravity, and seismological observations. Station A was occupied at 77°33′S, 158°30′E, at an elevation of 7750 ft, Station B at 77°09′S, 155°05′E and an elevation of 8300 ft, and Station C at 77°22′S, 139°48′E, elevation 8850 ft. Results obtained at these and other stations occupied in this program will be compared and correlated with those obtained on the oversnow traverses.

A combined New Zealand-United Kingdom Trans-Antarctic Expedition, using the US-IGY South Pole Station as a linkage point, was conducted during the past Antarctic summer, completing the first continental crossing of the Antarctic.

The New Zealand group, under the direction of Sir Edmund Hillary, left Scott Station (N. Z.), at the northwest corner of the Ross Ice Shelf, on October 14, 1957. Its purpose was to establish supply dumps for the United Kingdom party. It reached the Pole, about 1200 mi distant, on January 4, 1958. The United Kingdom party, led by Vivian E. Fuchs, left Shackleton Station, on the Weddell Sea, on November 24, 1957; it arrived at the South Pole on January 19, 1958. This was the first time the regions between the Weddell Sea and the South Pole, a distance of more than 2000 mi, had been crossed overland.

The party left IGY South Pole Station on January 24, and reached Scott Station, the terminus of the traverse, on March 1, 1958. Seismic studies made by the Fuchs party should provide the first profile of the ice thickness, surface elevations, and subglacial surface across Antarctica from the Weddell Sea to the Ross Sea.

During the 1957–58 summer season, USSR-IGY oversnow trail parties conducted traverses into the interior of Antarctica from IGY Mirny Station, on the Queen Mary Coast in East Antarctica; their goal was to establish scientific stations at the south geomagnetic pole and the "pole of inaccessibility." One party reached 78°27′S, 106°52′E, a few miles from the geomagnetic pole, on December 16, 1957. The USSR-IGY Vostok II Station was established at this location, 10,500 ft above sea level. This party reported winds up to 134 mph at a point along the traverse route 200 mi west of Mirny. Another party reached 78°24′S, 87°35′E, about 425 mi from the pole of inaccessibility, on February 12, 1958, where it established the USSR-IGY Sovietskaya Station. This station, deep in the interior of Antarctica, is at an elevation of about 12,100 ft.

Planned US-IGY Traverses

Personnel of IGY Little America, Byrd, and Ellsworth Stations will conduct further oversnow traverses during the 1958–59 Antarctic summer. The Little America group plans a roughly diamond-shaped traverse route on the Rockefeller Plateau north and west of Byrd Station, from 80°S, 140°W to 77°S, 130°W; from there to 80°S, 125°W in the vicinity of Byrd Station; then back to the starting point.

The Byrd Station party will cover a route in the southern part of the Ellsworth Highland, from the station to about 81°S, 75°W, to occupy a point first occupied by the 1957–58 Ellsworth Station traverse. It will then proceed to Horlick Mountain, at 85°S, 90°W, and back to Byrd Station. The total distance to be covered on the Byrd Station traverse is 1065 mi.

The route originally proposed for the 1958–59 Ellsworth traverse is heavily crevassed. As a result, alternative routes are under consideration.

Organization and Logistics

Each major US-IGY traverse party was staffed with two glaciologists (except the Ross Ice Shelf party which had three), two seismologists, one gravity observer, and support personnel. In each party were personnel capable of driving and maintaining the vehicles, navigating, operating and maintaining radios, cooking, administering first aid, and maintaining a field camp. Additional scientific personnel were added occasionally for special studies.

Indispensable airborne and other logistic support for the traverses was supplied by U. S. Navy Task Force 43 under the command of Rear Admiral George Dufek.

The vehicles used were Tucker Model 743 Sno-Cat Freighters, US Army M29C Weasels, and cargo sleds. Each Sno-Cat is capable of hauling 2300 lbs of cargo and passengers and of towing up to 2½ tons at cruising speeds of 10–15 mph. The four-passenger Weasels can tow sled loads of as much as two tons. The Sno-Cats and Weasels are equipped with heated cabs for both living and working quarters. During the 1957–58 traverses, each party used three Sno-Cats towing cargo sleds.

Lead vehicles of all traverse parties were fitted with electronic crevasse detectors to assist in finding safe routes. Gyrocompasses, which permit navigation independently of the earth's magnetism, were used instead of magnetic compasses, generally very unreliable in polar regions. Each oversnow traverse party carried one high-frequency radio transmitter having a range of .35 to 9.05 mc and capable of 125-watt CW (continuous wave) or 40-watt voice transmission. At least one medium-to-high frequency receiver was also carried by each party, as well as a portable 100-watt unit capable of 2- to 18-mc CW or voice transmission and reception.

Ski-equipped aircraft were used in advance of the traverse parties to help them choose the easiest and safest routes, providing reports and aerial photographs of the terrain to be crossed.

Experience has shown that such oversnow traverse parties can operate for distances of about 300 mi on the fuel they can carry. Hence, the total range of operation, 1200 mi or more for the major traverses, depended on airborne fuel depots established at the required intervals and on airdrop support when needed. In other respects, each traverse unit was as self sufficient as possible, carrying with it spare radio equipment and emergency gear to be used in case a vehicle was lost or damaged.

Physical obstacles, such as crevasse fields, and scientific considerations dictated some departures from original traverse routes.

World Warning Agency Decisions

October 3, 1957–January 1, 1958

During the first three months of the IGY, 14 periods of Alerts and 4 SWI (Special World Intervals) were declared by AGIWARN, the IGY World Warning Agency, operated by the National Bureau of Standards at Fort Belvoir, Virginia, near Washington, D. C. (See *Bulletin No. 5, November 1957*, for details of this first three-month IGY period.)

During the next three-month period, solar activity was in general lower; only six periods of Alert, totalling 23 days, and two SWI, totalling four days, were declared. One of the SWI was unsuccessful in that no major solar disturbance with associated terrestrial effects followed. During the other SWI a short but relatively severe geomagnetic disturbance took place.

In the second three months, sunspot activity, as measured in terms of the provisional Zurich monthly sunspot number, continued high, and the smoothed sunspot number continued to rise.

Following are the Alerts, SWI, geomagnetic disturbances, and major flares that occurred from October 3, 1957, to January 1, 1958. Alerts and SWI are numbered according to a simple chronological system in use by AGIWARN. The numbers in this list continue serially from the last Alert, number 10, which started on September 27, and the last SWI, number 6, which started on September 12, 1957. (The list of Alerts and SWI which appeared in *Bulletin 5*, p. 14, may be modified to reflect this numbering system.)

Oct. 9 034x Class 3 flare
Oct. 14 1600 Alert #11 starts
Oct. 16 0152 Class 3 flare; sudden ionosphere drop-out and gradual recovery
Oct. 16 0416 Class 3 flare
Oct. 19 064x Class 3 flare
0700 Class 3 flare

Oct. 20 1600 Alert #11 finishes
1637 Class 3+ flare
1644 Class 3+ flare
1700 Class 3 flare; sudden ionosphere drop-out and gradual recovery
Oct. 21 1600 Alert #12 starts
Oct. 22 0001 SWI #6 starts
Oct. 23 062x Class 3 flare; sudden ionosphere drop-out and gradual recovery
1600 Alert #12 finishes
2359 SWI #6 finishes
Nov. 12 1600 Alert #13 starts
Nov. 15 1600 Alert #13 finishes
Nov. 24 0848 Class 3+ flare
1600 Alert #14 starts
Nov. 26 0001 SWI #7 starts
1455 Moderate magnetic storm starts
Nov. 27 12xx Magnetic storm finishes
1600 Alert #14 finishes
2359 SWI #7 finishes
Dec. 5 065x Class 3 flare
Dec. 14 125x Class 3 flare
Dec. 15 1600 Alert #15 starts
Dec. 16 1127 Class 3 flare
Dec. 18 0450 Class 3 flare
Dec. 21 1600 Alert #15 finishes
Dec. 26 1600 Alert #16 starts
Dec. 29 1600 Alert #16 finishes

As an illustration of how AGIWARN uses information and advice from other centers, an excerpt from a report by R. C. Moore, Director of AGIWARN, is given below. The code groups have the following meaning:

ALNIL—No Alert
ALBEG—Alert begins
ALCON—Alert continues
ALFIN—Alert finishes
INBEG—SWI begins
INCON—SWI continues
INFIN—SWI finishes

"For several days prior to November 22 the sun was relatively quiet. Without exception the nine centers (Anchorage, Boulder, Darmstadt, Kokubunji, Moscow, Nederhorstdenberg (NERA), Paris, Prague and Sydney) advised that no Alert be started (ALNIL); the AGIWARN decision on each of these days was ALNIL.

November 22: Eight centers suggested ALNIL, while Sydney wanted to begin an Alert (ALBEG). A solar region then well west of central meridian produced several flares, but none of great interest. The AGIWARN decision was ALNIL.

November 23: Seven centers advised ALNIL; Moscow's advice was ALBEG; no message was received from Paris. The western region's activity level appeared to be rising, but the situation did not seem to warrant the starting of an Alert, so the AGIWARN decision was ALNIL.

November 24: Boulder, Moscow and NERA advised ALBEG; Anchorage, Darmstadt and Prague advised ALNIL. Kokubunji and Sydney suggested ALBEG also but the messages arrived too late, and no message was received from Paris.

By now the western region was no longer active, but an eastern area which had appeared at the east limb of the sun November 20 and had exhibited only minor activity during the first four days of its transit suddenly became interesting. It produced a series of flares ranging in importance from 2 to 3 plus. This flare activity was accompanied by well observed major radio noise events.

Based on the above activity, plus encouragement from three of the six centers, AGIWARN began an Alert.

November 25: Five centers advised that the Alert be continued (ALCON) and four centers (Darmstadt, NERA, Paris and Sydney) suggested that a Special World Interval be started (INBEG).

Although only one of the four centers (NERA) which suggested INBEG had advised ALBEG the preceding day, the timing of the events which had precipitated the November 24 ALBEG seemed to warrant the starting of an Interval. The AGIWARN decision, therefore, was INBEG.

November 26: The Interval began at 0001 UT and a sudden commencement of geomagnetic disturbance started at 1455 UT. Eight centers advised that the Interval be continued (INCON) and one (Paris) suggested it be finished (INFIN) but the Alert continued (ALCON). The AGIWARN decision was INCON.

November 27: Five centers advised that the Interval be stopped but suggested that the Alert be allowed to continue. Four centers (Darmstadt, Moscow, Prague and Sydney) thought that the Interval should continue.

The region associated with the disturbance had produced no major flare activity since November 24. In addition, the storm appeared to be subsiding quickly. The AGIWARN decision, therefore, was ALFIN INFIN.

November 28: The disturbance was officially ended about 1200 UT November 27. All centers advised ALNIL and the sun continued to be quiet. The AGIWARN decision was ALNIL."

Cosmic-Ray Balloon Experiments

Soft Radiation Associated with Auroras and Geomagnetic Activity

As long ago as the summer of 1953, L. H. Meredith, M. B. Gottlieb, and J. A. Van Allen detected the presence of new "soft" (low energy) radiation at altitudes above 50 km by means of Geiger counters in a series of rockoon (balloon-launched rocket) experiments. During the summers of 1953, 1954, and 1955, Van Allen's group observed the latitude distribution and temporal variation of the effect; these strongly suggested that it was auroral-associated, even though all flights were made in the daytime, and no direct correlation with visual auroras could be shown.

Using additional experimental data taken with a scintillation detector, Van Allen concluded that the soft radiation was probably X-rays in the 10–100 kev (1–0.1Å) range rather than protons or electrons. This was supported by laboratory experiments and energy calculations which suggested that the X-rays might be produced as "bremsstrahlung" from incoming electrons penetrating to 90–110 km in the atmosphere. (When a particle having kinetic energy in the X-ray range suffers a collision with an atom, and this energy is released in the radiant form, it is termed "bremsstrahlung," literally "the deceleration or braking radiation.") The soft radiation detected would therefore have been created in the atmosphere rather than incident upon it from outside, as in the case of low-energy cosmic rays themselves.

In the course of the first few months of the IGY, two series of cosmic-ray balloon flights have demonstrated that soft radiation is sometimes present at much lower altitudes in the atmosphere. One series of 20 flights launched at Minneapolis during July, August, and September 1957 was conducted by E. P. Ney and J. R. Winckler of the University of Minnesota to provide week-by-week checks of cosmic-ray intensity and also to coordinate with other IGY cosmic-ray balloon programs in the field. Among the latter was a series of flights at Fort Churchill under the direction of Kinsey Anderson of the State University of Iowa. The following is a brief summary of some of the more significant observations of soft radiation and associated events made on these flights. Recent IGY rockoon observations of auroral soft radiation, made by Van Allen, were reported in *Bulletin No. 5, November 1957*.

The high level of solar activity during the beginning of the IGY produced a number of auroral displays of great intensity. During three of them, on July 1, September 12, and September 21–22, 1957, the Minnesota workers were successful in placing a balloon at high altitude during the aurora and observing soft radiation at levels corresponding to pressures from 8 gm/cm^2 to 40 gm/cm^2. (In an isothermal atmosphere at 273°K, or 0°C, these pressures would correspond to altitudes of 38.9 km and 26.1 km, respectively. At higher or lower absolute temperatures, the corresponding altitudes are proportionally greater or lower than those cited.) Instruments flown on these occasions were an ionization chamber, a single Geiger counter, and, on September 22, a special photon counter.

J. R. Winckler and L. Peterson of Minnesota have reported that during the flight of July 1 an aurora began at 0330Z while the balloon was floating at the 8 gm/cm^2 level. A large initial ionization burst of ten minutes' duration occurred, followed by a weaker one lasting fifteen minutes and another, still weaker, peaked at 0420Z. Fluctuations were seen until 0630Z in both the ionization chamber and Geiger counter. The large initial effect was associated with auroral rays near the zenith, and the increases in rates were roughly correlated with visual observations of increased brilliance near the zenith.

It should be emphasized that this was the first recorded instance of a directly observ-

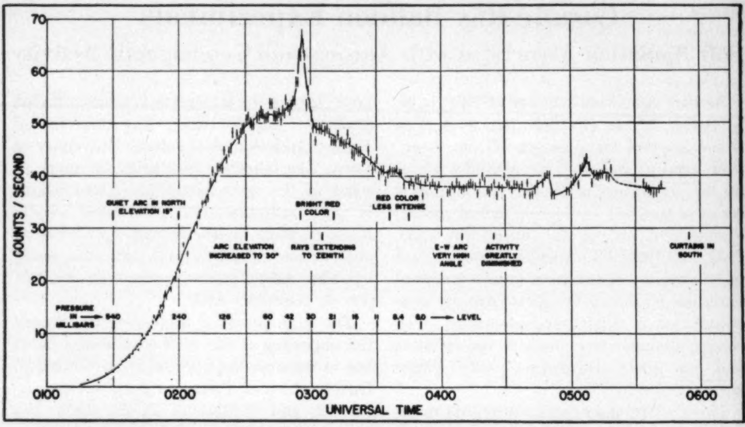

Fig. 2. Geiger counter record taken on a balloon flight at Minneapolis during the auroral display of September 12, 1957. One millibar of pressure is equivalent to 1.08 gm/cm².

able correlation of visual aurora and soft radiation, although, as noted above, the distribution and variation of the kind of radiation observed by Van Allen some years earlier implied a close connection with visual auroras.

In Figure 2, the graph of Geiger counter data obtained on September 12 shows a clear correlation with visual auroral phenomena. A smooth steep rise, middle altitude maximum, and decline to a steady counting rate is typical of a quiet-day record as the balloon rises to altitude. On this day, however, a large increase occurred at the relatively low level of 40 gm/cm²; other deviations from quiet-day behavior are shown by the fluctuations of the line drawn through the observational points. A peak X-ray intensity above the atmosphere of 500 milliroentgens/hour was estimated from data obtained on this flight.

In the July 1 experiment, both the integrating ionization chamber and single counter recorded strong bursts with large fluctuations. The ratio of the two rates—the relative mean ionization per count—varied from 0.2 to 0.26 prior to the commencement of the auroral effect, but during this effect the ratio of the excess rates was 1.3 to 1.4. The value of 0.2 is characteristic of fast, singly-charged particles in the lower atmosphere, while the increase to 0.26 at higher altitude was attributed to increased flux of heavy primary nuclei at those levels. Laboratory studies of the ratio of ionization per count for X-rays of various energies and for gamma-rays showed that the experimental observation of a ratio of 1.4 under 8 gm/cm² of atmosphere is consistent with X-rays in the energy range 50–70 kev. These X-rays are attributed to electrons moving at one half the velocity of light and emitting bremsstrahlung in the high atmosphere.

A balloon flight made from Fort Churchill, Manitoba, directed by Kinsey Anderson on August 29, 1957, has provided other remarkable evidence of the close interrelations of cosmic rays, soft radiation, and geomagnetic activity—although in this case no direct relationship with auroras was demonstrated. The balloon was instrumented with a vertical-counter telescope, a single counter, and a Neher-type ionization chamber.

A record of the data obtained is presented in Figure 3. The level at time A is the steady pre-storm cosmic-ray level; at B, soft radia-

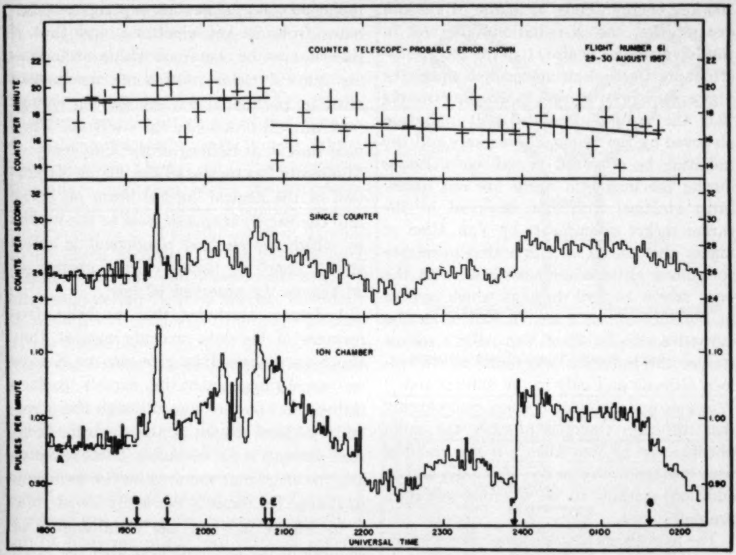

Fig. 3 Cosmic-ray and soft-radiation intensities over Ft. Churchill during the magnetic storm of August 29, 1957. (Reprinted from Journal of Geophysical Research, vol. 62, No. 4 [1957]).

tion begins to appear in both the single-counter and ionization-chamber records at the time when a magnetic storm commenced outside the auroral zone. The subsequent fluctuations of soft radiation, as shown by these records, were accompanied by a magnetic storm with changes in field as large as 400 or 500 gammas, beginning at Fort Churchill at time C. An intense burst of 30-mc radio noise was observed there at time D. An abrupt Forbush-type decrease depressed the counting rates of all these instruments after time E, but a very sharp increase in soft radiation took place at time F; it should be noted, however, that since the ionization chamber and single counter also count soft radiation, the drop at this time is not so apparent in them as in the counter telescope. It was accompanied by a large and rapid decrease of the vertical component of the earth's magnetic field observed at Fort Churchill. At time G, the sun set on the balloon, which began to sink rapidly. No unusual auroral activity was observed, except for a stationary region of low intensity on the evening of August 30, although a display of rayed bands was seen the following night.

The stopping power of the vertical counter telescope was less than that of the ionization chamber. Hence, incoming soft radiation in the form of charged particles should have been observed in it as well as in the other two instruments. It is therefore significant that no soft radiation was observed in the vertical counter telescope, and it was concluded that the soft radiation could only consist of X-rays with energies no greater than 700 kev.

Simulation experiments with X-ray sources at the State University of Iowa have shown that the relative response of the ionization chamber and single counter could be reproduced by X-rays of approximately

100 kev energy. Thus, as in the Minnesota experiments, the X-radiation observed in the Iowa studies is also attributed to bremsstrahlung from electrons incident upon the atmosphere from outside. Anderson remarks that the auroral-associated soft radiation observed by the Minnesota workers and the radiation he observed at balloon altitudes during the magnetic storm are not necessarily identical with that observed in the earlier rocket experiments by Van Allen at higher altitude. (The X-rays that penetrate to balloon altitude are associated with the very active auroral displays which appear in the sub-auroral zones as well as in the auroral zones. In all of Van Allen's rocket studies the radiation was found above balloon altitude and only in the auroral zone.) Winckler and Peterson concur, commenting that although theirs is possibly the same phenomenon as Van Allen's, it is correlated with visual auroras for the first time, and in addition appears to be a more energetic process.

The hypothesis that electrons are responsible for the creation of soft radiation raises the question of their origin. Winckler and Peterson favor the assumption that the soft radiation observed in their experiment originates from 60 kev electrons, and that if these cannot be contained within an incoming auroral beam itself some mechanism must be postulated for transferring energy from auroral protons to the electrons. They note that P. J. Kellogg of the University of Minnesota has suggested the charge separation of the neutral auroral beam on entry into the earth's magnetic field as the means by which the electron component is accelerated from its beam-velocity energy of 30 kev to the observed 60 kev.

Anderson concludes that at least two features of his data strongly suggest that electrons presumed to give rise to X-rays are accelerated near the earth's surface rather than on the sun, although the possibility of local release of the electrons from solar streams is not excluded. These features are: the short time required for the radiation to change its intensity markedly (as at time F in Figure 3), and the simultaneity of changes in the soft radiation with the large storm-type decreases in the earth's magnetic field.

Earth-Strain Measurements in South America

Two fused-quartz extensometers, relatively new instruments for measuring earth strain, have been installed at locations in the Andes Mountains as part of the US-IGY program in seismology. The project is directed by Hugo Benioff of the California Institute of Technology. The observing stations are operated by the University of Chile and the Peruvian National Committee for the IGY.

Standard seismometers, which have been used since the late 19th century, record ground motion during the passage of elastic waves, whose source may be either an earthquake or an artificial explosion. The extensometer, or strain seismometer, on the other hand, measures the differential motion between two nearby points (the ends of the extensometer). The change in the length of the extensometer, either increase or decrease, when divided by the original length, represents the change in strain.

The first extensometer employed for routine observations was designed and installed by Benioff more than 20 years ago. This instrument used an iron pipe as a length standard and a moving-coil-type electromechanical transducer. About 10 years ago, a redesigned version, using a fused-quartz rod as a length standard and a capacity bridge transducer, was installed at Isabella, California. The quartz rod greatly reduces undesirable variants caused by temperature fluctuations, and the capacity bridge increases the response of the extensometer to include waves of very low frequencies (or long periods). The South American extensometers are of this type.

The extensometers will provide three kinds of observational data: measurements of secular (long-range) strain changes occurring in the great Andes mountain range; measurements of the tidal (diurnal) strains of the earth produced by the gravitational action of the sun and moon; recordings of ultra-long-period seismic waves, including possible free vibrations of the earth excited by earthquakes.

Measurements of secular strains and their accumulation, made at an adequate number of stations over a long interval of time, may yield sufficient information to determine the strain pattern and habit of a region. It is conceivable that such knowledge might ultimately provide a basis for the prediction of earthquakes. The time required for such a study, however, might well run into several centuries.

Measurements of tidal strain provide information on the elastic and plastic properties of the outermost portion of the earth. The long-period waves yield information concerning the mantle and core of the earth as well as the mechanism of the generation of earthquakes.

One of the new extensometers is located at San Cristobal, in the outskirts of Santiago, Chile; the other is in Chosica, a small settlement some 20 miles from Lima, Peru. The University of Chile, at Santiago, and the Peruvian National Committee for IGY, at Chosica, have excavated the tunnels in which the instruments are located, are providing electric power at the sites, and are supplying personnel for the operation of the stations.

Cinna Lomnitz, a member of the staff at the University of Chile, is local scientific advisor for the Santiago work. J. A. Broggi, Chairman of the Peruvian National Committee for IGY, is the scientific advisor at Chosica.

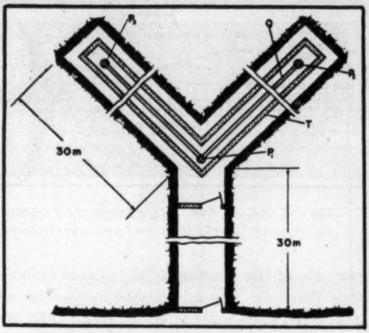

Fig. 4. *Schematic Plan View of the Extensometer Installation at Chosica, Peru.*

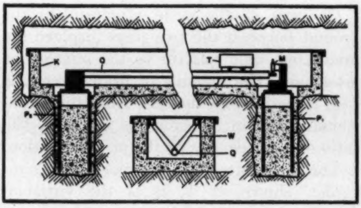

Fig. 5. *Schematic Vertical Section of One Extensometer Component.*

Each installation consists of two horizontal extensometers mounted at right angles in tunnels bored into igneous rock (see Fig. 4). The length standards are constructed of fused-quartz tubing with outside diameters of 2.5 inches, 0.25-inch walls, and lengths of 25 meters.

The mounting of the standards is shown above in a schematic vertical section through one component (Fig. 5). P_1 and P_2 are piers constructed of sections of 12-inch steel pipe sunk into the rock and cemented in with concrete. The quartz standard, Q, is rigidly fastened to one pier and is supported by a series of stainless steel wires, as shown by W in the inset. These prevent transverse movements of the quartz standards without exerting effective longitudinal constraints. Secular measurements are made with the measuring microscope, M, mounted on the

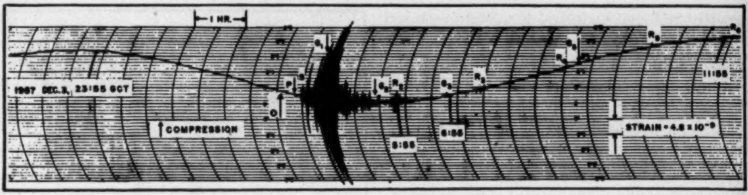

Fig. 6. *Record from Extensometer at Isabella, California. Vibrations set up by the Mongolian Earthquake (Δ = 10,000 km) are superimposed on the trace of the semidiurnal earth tide.*

pier, P_1, at the junction of the quartz standards (Fig. 4). The microscope focuses on a graduated glass scale mounted on the end of the quartz tube. (There are actually two microscopes at P_1, one for each quartz standard.)

Changes in the state of strain in the ground between the two piers displace the graduated scale relative to the microscope cross-hair. The amount of displacement is read directly from the scale, and the corresponding strain increment is given by the ratio of displacement to the pier separation.

The transducer for the tidal strain recorder, shown at T, is of the variable-capacity, resonant-bridge type and operates with a carrier frequency of 5 mc. It is constructed with transistors exclusively. Output from the transducer actuates the ink-writing recorder.

Fused quartz was chosen for the standards because of its low thermal expansion (about 5×10^{-7} per degree C) which, with the expected annual temperature variation within the tunnel of not more than one or two tenths of a degree, should permit secular strains to be measured with an accuracy of approximately one part in 10^7. However, since the diurnal temperature variation of the tunnel is very much smaller, tidal strains can actually be measured to within about one part in 10^9.

Recordings made with the extensometer tidal-strain recorder at Isabella, California, indicate that the sensitivity of the transducer recorder assembly is such that one division on the record represents a strain increment of 8.6×10^{-10}—equivalent to $\frac{1}{10}$ inch in 2000 mi. The South American tidal strain recorders are similar to this one in design and are expected to produce similar recordings.

Figure 6 is a record from the Isabella instrument showing the twelve-hour tidal period for December 4, 1957. Superimposed are the strains from the large (magnitude 8.5) Mongolian earthquake of the same date. The letters G and R on the record refer to Love- and Rayleigh-type seismic waves, respectively. These waves have travelled along the outermost portion of the earth's mantle, just beneath the relatively thin crust (10–50 km thick), from their earthquake source to the instrument site. Such waves travel outward from the disturbance in all directions, commonly circling the earth a number of times.

Love waves travelling the shortest arc to the instrument (10,500 km) are here designated G_1. Love waves travelling the longest arc (29,500 km) are designated G_2 and Rayleigh waves travelling the longest arc are designated R_2. The second passages of the short-arc waves are shown by G_3 and R_3, and of the long-arc waves by G_4 and R_4. Symbols representing subsequent passages have correspondingly higher subscripts. The time of origin of the quake is represented by 0. P and S indicate the first arrival of compressional and shear waves, respectively, which have penetrated the mantle to considerable depth.

Volunteer Satellite Tracking by Radio

The primary method employed in the US-IGY program for radio tracking of earth satellites is the Minitrack system described in *Bulletin No. 2, August 1957*. Two other tracking systems are also in use in a volunteer supporting program designated Moonbeam. One, a simplified version of the prime Minitrack system, is designated Minitrack Mark II. The other, developed by the Jet Propulsion Laboratory of the California Institute of Technology, is called Microlock. It is used in conjunction with the JPL receiving system. Like Minitrack, both Minitrack Mark II and Microlock use the interferometer principle (measurement of the phase difference of signals received simultaneously at different antennas) to determine the angular position of the satellite. The principle of angular position determination by interferometer measurement is explained in the report cited above.

Minitrack Mark II

The Minitrack Mark II is a relatively inexpensive system which can be built and installed with the resources available to many serious volunteer groups. The Mark II system in its simplest form is diagrammed in Figure 7. In this form, the Mark II provides only a meter indication of the presence and passage of the satellite.

This basic system can be modified to provide information accurate enough to be used in computing orbits. A block diagram of such a modified system is shown in Figure 8. When 1000-foot baselines are used and a precise time signal is recorded simultaneously with the interferometer data, this system can give time indications of satellite positions for approximately each quarter of a degree of satellite travel parallel to the base line.

Although the phase difference data recorded by the Minitrack Mark II system may give ambiguous positions, these ambiguities can be resolved at the Computing Center by reference to data gathered by prime Minitrack stations.

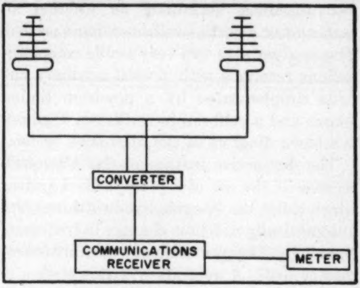

Fig. 7. *Simplest Form of Mark II Minitrack System.*

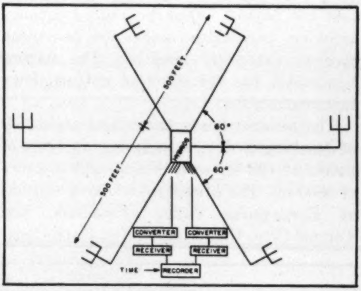

Fig. 8. *Advanced Mark II Minitrack System*

Minitrack Mark II stations are capable of tracking both the 10-milliwatt and the 60-milliwatt transmitters of 1958α to an accuracy of 45 seconds of arc and one millisecond in time. The 10-mw signal at 108.00 mc is preferred for accuracy in tracking, but the 60-mw signal at 108.03 mc is more easily received by most volunteer stations. To be of scientific value, a volunteer radio observation should be accurate to at least one milliradian, or 3½ minutes of arc.

Microlock

The Microlock system uses a variety of antenna arrangements. For the tracking of $1957\alpha2$ three antennas arranged in a right triangle were used. The antenna forming the vertex of the triangle is used as a common point in combination with either of the other two antennas, depending on whether an east-west or a north-south base line is needed. The receiver uses two very stable communications receivers with several auxiliary circuits supplemented by a precision timing source and a calibration oscillator. Figure 9 is a block diagram of the Microlock system.

The distinctive feature of the Microlock receiver is the use of a phase-locked system which shifts the 10-cycle bandwidth receiver automatically to follow changes in frequency caused by Doppler shift or transmitter-frequency drift. A byproduct of this system is an automatic recording of Doppler data. Figure 10 shows the basic phase-locked loop. The use of the phase-locked system and the narrow (10-cycle) radio-frequency tracking bandwidth makes the Microlock receiver extremely sensitive. The narrow bandwidth has the effect of cutting down extraneous noise.

The receiver has a theoretical capability of tracking a device radiating one mw of power at 108 mc at a line-of-sight distance of 3000 mi. The Microlock tracking stations at Earthquake Valley, Pasadena, and Temple City, California, and at Cape Canaveral, Florida, have tracked the 10-mw signal of 1958α at even greater distances.

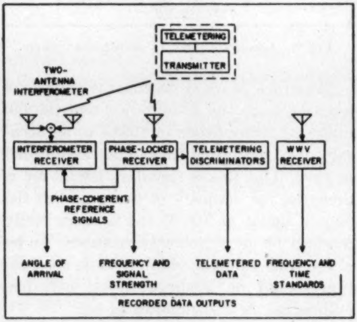
TELEMETERING
TRANSMITTER
TWO-ANTENNA INTERFEROMETER
INTERFEROMETER RECEIVER
PHASE-LOCKED RECEIVER
TELEMETERING DISCRIMINATORS
WWV RECEIVER
PHASE-COHERENT REFERENCE SIGNALS
ANGLE OF ARRIVAL
FREQUENCY AND SIGNAL STRENGTH
TELEMETERED DATA
FREQUENCY AND TIME STANDARDS
RECORDED DATA OUTPUTS

Fig. 9. *Block Diagram of Microlock System*

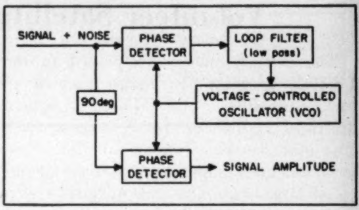
SIGNAL + NOISE
PHASE DETECTOR
LOOP FILTER (low pass)
90deg
VOLTAGE - CONTROLLED OSCILLATOR (VCO)
PHASE DETECTOR
SIGNAL AMPLITUDE

Fig. 10. *Basic Phase-Locked Loop*

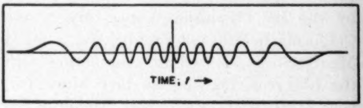

Fig. 11. *Interferometer Signal During Satellite Transit.*

The output of the tracking receiver and a time reference are fed into a pen recording trace from which the time of crossing of the meridian or parallel can be derived. Figure 11 shows a typical trace of a satellite passage.

The Microlock receiving system can also be used to receive 40-mc signals, one of the frequencies used by USSR satellites. To convert the system to reception of 40 mc, add a mixer to accept the 40-mc signals from the antenna. The communications receiver is then tuned to the difference frequency (2.3 mc) between the 40-mc signal and the output of the local oscillator (42.3 mc). With these changes the system will track the 40-mc satellite transmitter in the same manner as described above for the 108-mc transmitter.

Individuals and groups interested in participating in the Moonbeam volunteer radio tracking program may obtain information on the program by writing the National Academy of Sciences, IGY Earth Satellite Office, 2101 Constitution Ave., Washington 25, D. C.

Transactions
American Geophysical Union

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Twentieth Award of the William Bowie Medal

Citation of Johannes Theodoor Thijsse

Prepared and Presented by WALTER H. BUCHER

This citation was to have been written and personally read by Hilding Beij, our former General Secretary who, as a hydrologist, is personally well acquainted with Professor Johannes Theodoor Thijsse and his work. To our deep regret, illness that led to an operation has made this impossible. When, as Chairman of the Committee, I was called upon to take his place, I turned to the letters in the Committee's files which help us in making final decisions. I shall quote primarily from a letter contributed at our request, at the time of our deliberations, by Prof. J. M. Burgers, at present of the Institute for Fluid Dynamics and Applied Mathematics at the University of Maryland, a former colleague and Professor Thijsse's fellow member of the Royal Netherlands Academy. You will find the main biographical data concerning the medalist in the brochure which you received at the entrance.

After obtaining his degree from the Delft Technical University in 1918, Thijsse became Executive Engineer of a Commission instituted by the Netherlands Government which was to investigate how far the closing of the Zuider Zee, Netherlands' shallow inland sea, would influence the height of the tides, especially the storm tides, on the coast of the province of Friesland. Here Thijsse worked in close cooperation with the Commission's president, H. A. Lorentz. This close cooperation with the famous theoretical physicist has been a decisive influence in Thijsse's scientific development.

Johannes Theodoor Thijsse
Recipient, Twentieth Award
William Bowie Medal, May 6, 1958

Lorentz succeeded in developing a method of calculation for the tidal motion in a network of shallow channels and basins, such as exist in the Zuider Zee and the waters between the Zuider Zee and the North Sea, where bottom traction is an important factor. This method took into account non-linear effects and was designed so that the influence of the wind could be taken into account. Thijsse carried through all the necessary measurements in the preparatory stage of the work and soon took part in working out the calculations. During the construction of the main dike closing in the Zuider Zee, Thijsse was constantly engaged in making further measurements, to check the predictions of the theory and to get further data.

This work did not only yield essential information concerning the effect of the main dike on the height of the storm tides on the Frisian coast, but gave at the same time most valuable information on what could be expected from the tidal motion while the construction was in progress.

Since then, the application of the methods of calculation developed by Lorentz and Thijsse and their coworkers has become a standing part of engineering practice in connection with reclamation projects and other constructive enterprises on The Netherlands coast and, in general, in those parts of river courses which are affected by tidal motion.

The vastly complex project of draining the Zuider Zee was based on model experiments carried out chiefly in Professor Rehbock's famous hydraulic laboratory in Karlsruhe, Germany. While the actual work was in progress, Thijsse was charged with the task of creating a hydraulic laboratory in The Netherlands in which to continue the model experimentation with which to direct the field projects. The laboratory was opened in 1927 in the basement of the Department of Civil Engineering of the Technical University at Delft, with Thijsse as its Director. Soon the amount of research to be carried out increased to such an extent that a separate building had to be erected which was opened in 1933. It was given a special form of management which made it formally independent of the Technical University while all scientific connections were maintained. In 1938, Thijsse was appointed part-time Professor of Theoretical and Experimental Hydraulics at the Technical University. In 1946, he was made full Professor. In 1948, he was elected a member of the Royal Netherlands Academy of Sciences.

In the many problems of hydraulics that have been studied in the laboratory, great care was always taken to treat fully the purely scientific side of each problem. He passed on to all who worked under him what he himself has called the chief lesson Lorentz had taught him: to approach every practical problem by digging back to the fundamentals of theory.

Among the problems investigated in the laboratory are those of influence of the wind on the water, especially the formation of waves; the action of waves, both in canals and in basins, with special attention to the problem of bed load and the various model ratios needed in experimentation; and, finally, the application of the basic knowledge gained to the protection of dikes and ports against heavy tides or swells. For such complex model experiments a special wind tunnel of large dimensions was constructed which has now been superseded by a still larger one that is under construction in the *Noort-oost Polder* near Vollenhave in the Netherlands, where open air facilities are available for making experiments with large amounts of water.

Thijsse's leading position in hydrology rests on these fundamental researches and their effective engineering application. The Bowie Medal honors an additional distinction; a breadth of interest and a consequent willingness to give of one's time and knowledge to colleagues working in other fields of science.

Thijsse's father was one of the important biologists of the Netherlands, who did much to promote a general interest in observational biology—an interest which our medalist has maintained all his life. It has influenced many a decision of the board for the reclamation of the Zuider Zee which he directed in the interests of biological ecology. To quote one characteristic action: Thijsse saw to it that filling material that had to be disposed of, was used to build an island designed to serve as a bird refuge.

Thijsse took an active interest in the geological and geophysical aspects of the changes in sea level that have followed the removal of the Pleistocene ice load from Scandinavia. Together with Professor Vening Meinesz and the late Professor Umbgrove, he has studied the detailed evidence produced by Pleistocene geologists of Scandinavia. Burgers wrote that since Thijsse became a member of the Royal Society, he was always to be found at the table where geologists, paleontologists, biologists, and members from other disciplines were collected, a group which Burgers frequently joined, and where Thijsse's opinions and advice were always eagerly sought.

Professor Martin Rutten wrote,"... as a council member of our Dutch geographical society, Thijsse has always made available his experimental work and his keen insight to geographers, pedologists, and geologists.... I remember well a stimulating lecture of his, given some four years ago, under the title of *The Map of Holland in the 21st Century*. In Toronto, last September, Thijsse agreed to go with geologists into the question of ebb and flood in the very wide, very shallow shelf seas such as must have been in existence in Mesozoic and Paleozoic times."

This breadth of vision and comprehension of the problems that men in other disciplines face is the criterion for the award of the Bowie Medal—designed to encourage "unselfish cooperation in research."

In 1952, Thijsse was invited to give a semester course at the University of Michigan—where Vening Meinesz, another Bowie Medalist, will give a semester's course next Spring. However, in February, 1953, he was called back telegraphically by The Netherlands Government to give his help in coping with the disasters brought about by the catastrophical sea surge and flood.

Since then, Thijsse has been in charge of much of the work that had to be done to repair the damage. Experience with the problems that confront the engineer in this field had been obtained already in closing the gaps in the dikes at Walcheren which had been made by the Allied Command near the end of the war in order to force the German troops out of the island. And again, in all this work, a difficult type of engineering work which requires the highest skill from all men involved, from captains as well as the personnel of dredges and tugboats, the guiding line of action was laid down by Thijsse—on the strength of his knowledge gained from his theoretical work and of the practical knowledge derived from the model experiments in his laboratory.

No wonder the Netherlands Government bestowed honors on him. For his share in dewatering Walcheren Island, he was made a Knight of the Netherlands Lion. Many other honors have come to him.

We honor him because as a leader in hydrologic physics and engineering he has maintained a wide perspective over many problems in other fields of science and stimulated thought and given advice to fellow workers in other disciplines. Mr. Vice President, it is a great privilege and pleasure to present to you Professor Johannes Theodoor Thijsse for the Bowie Medal.

Presentation

LLOYD V. BERKNER

Professor Doctor Engineer Johannes Theodoor Thijsse, by authority of the American Geophysical Union, and on behalf of President Ewing and the members of the American Geophysical Union, it gives me great honor and pleasure to convey to you the William Bowie Medal. This is the highest honor that we can award to our most distinguished colleagues.

Response and Acceptance, and Address: In the Borderland Between Geophysics and Engineering

J. TH. THIJSSE

It will be hardly necessary to say how grateful I am for the great honor which has been bestowed on me, especially to Dr. Berkner for the presentation of the William Bowie Medal and to Dr. Bucher for the citation.

I am sure that Dr. Berkner and Dr. Bucher will not mind when I declare that I am exceedingly sorry that the two persons whose names are printed in the program (President Maurice Ewing and K. Hilding Beij) and whose tasks they so graciously fulfilled, cannot be here tonight. Both Dr. Ewing and Mr. Beij are recovering from operations. You will agree with me that we all wish them to have a complete and speedy recovery.

Of course my achievements in geophysics have been exaggerated. Still I feel that, like several civil engineers in The Netherlands, I have done something in the line of oceanography and hydrology and that I have stimulated practical application of meteorology. I shall tell you how.

It takes a long time for an engineer to get familiar with geophysics. It is easier, however, if the engineer lives and works in a country which is so much affected by geophysical phenomena as The Netherlands, my home country.

The country is traversed by three rivers of some importance. One of them, the Rhine, carries the heaviest traffic in the world. The soil consists of thick layers of sand, clay, and peat, pervious to water. The surface of the land is slowly sinking in respect to the sea: at present great parts are situated below mean sea level. The consequence of this is that the ground water is brackish or salty and also that the country would be permanently flooded if the sea would not be kept out artificially.

The country is densely populated: six million dwell on six thousand square miles. These people have to live and, if possible, live in safety. The engineer has to see to that and the geophysicist helps the engineer in making his projects.

At the meeting of the International Association of Hydrology, IUGG, at Toronto in September 1957 I quoted an American meteorologist on the reaction of man on meteorological phenomena. I repeat it here, because I think it is true, not for meteorology only, but for geophysics in general. He stated that the first contact is in the realm of *superstition*. Later, from careful *observation* one finds an *explanation* of the phenomena. This may lead to *prediction* and eventually to *influencing*, which also may be called engineering. Superstition is not a subject for today; observation, explanation, and prediction are the work of the geophysicist, who leaves influencing to the engineers.

The tasks of the rivers is to carry their load of water, ice, silt, and sand safely to the sea and moreover to provide a continuous channel for navigation. In order to prevent flooding the ancient inhabitants built embankments, far enough apart and high enough to allow the maximum flood to pass. Hydrology did not yet exist at the time, so it could not give a definition of 'maximum flood.' Nevertheless the levees are in the places which we consider as correct at present. The question may be asked if our ancestors possessed a special instinct which guided them to this result.

After the levees were made the rivers did the usual thing, depositing silt on the floodlands every flood. Usually this leads to the consequence of raising the bed to an unacceptable level. No so in the case of Dutch rivers: the clay is dug away for the manufacturing of bricks, of which a stoneless country is greatly in need. Nor is there danger of raising of the main bed because the sand is dredged out and used for improving the stability of the soil where cities, roads, and airports are built, so navigation channels are maintained without extra cost. The rivers are in a good condition without the active help of geophysics.

It is different, however, in the case of the threat from the sea. This is influenced by the tides of the sea and its estuaries (oceanography), whipped to an extra high level by gales (meteorology). In the course of time the land has become lower and lower in respect to the sea level. Geodesists have to make observations on this phenomenon by successive accurate levelings. An explanation must be provided by studying the physics of the Earth's interior, by which also an attempt may be made at prediction.

It is now certain that the land has actually sunk and that the change has not been wholly due to rising of the sea level by recent melting of ice. Successive levelings have shown that tilting takes place: the northern part of the country is significantly lower than the southern part as compared with a century ago. The difference is about four inches.

Combining our observations with German and Scandinavian ones leads to the well-known theory that Scandinavia is still striving toward isostasy after losing its load of ice 20,000 years ago. The sima is being drawn from under the surrounding countries, the deepest depression being just north of Holland. Vening Meinesz, William Bowie Medalist in 1947, calculated the viscosity of the sima. There may be a complication by the 'melting' of the root under the Alps, but the effect of that is of minor importance. It is very probable that the rate of sinking, five inches per century in the south, nine in the north, is mainly caused by actual lowering; the rising of the sea level will be less than five inches per century.

On the strength of this, the prediction must be that the lowering will go on. The geologic effect will slow down, it is true, but only at a very small rate. This means that we must be prepared for higher sea surges than the present ones. A few inches every century does not sound very alarming, but in the long run it counts up. Twelve feet in two thousand years is a great deal; about the beginning of our era the surface of the land was high enough to be inhabitated without artificial means of defense against the sea. Prehistoric layers of peat, which are now situated far below sea level, can be accurately dated by means of the C^{14}

method, which shows that the average lowering during the past 70 centuries has been slightly more than the present rate.

The phenomenon is complicated by local compression of the soil and of the body of the levee itself. In some places the crest of the dikes sink an inch every few years.

This influences the defense system against the sea. Formerly each time the dikes were raised just enough to withstand a repetition of the last flood. Sometimes, when the economic position of the country was very good, they were raised a little bit more. After the gale of 1953, an attempt was made to find an economic optimum for the strength of the defense. Thus the principal man becomes the economist, who has to compare the cost of strengthening with the decreased risk of flooding. This cannot be done with any accuracy. Nobody knows the damage which will be brought about by a major flooding in the center of Holland. Also the frequency of very high floods is difficult to evaluate. There is a good record for 100 years and there are less reliable data extending over a period of six centuries. It appears that the optimum will be reached if the sea walls can withstand a gale and the consequent sea surge with a frequency of about 10^{-4} per year.

What is this level? Of course the statisticians have to provide an answer to that question, but they would be helpless without the aid of meteorologists and oceanographers. The trouble is that the data are not homogeneous; no two surges are alike. But rejecting part of the sample influences the extrapolation. I should like to have a thorough discussion on that subject at another time.

Instead of raising the embankment along the estuaries which penetrate deeply into the country, efforts are being made to shorten the coastline. The present stage is the Delta Project which plans to close five of these estuaries at their mouths. Previously we closed the Zuider Zee, banning the floods from the heart of Holland.

Operations like these greatly affect the tidal movement. At the beginning of the *Zuiderzeewerken* not very much was known about propagation of tides in shallow water. There were a number of observations, but the explanation was not satisfactory and so no prediction could be made as to the effect of influencing. Fortunately Lorentz, our greatest physicist since Huyghens, took charge of a panel of experts and indicated the methods which enables us to proceed with the work with eyes wide open.

In 1918 when the decision to enclose the Zuider Zee was made, it was not possible to construct the dam and the sluices therein in the actual coast line and a second line was selected, about 15 miles inland. New experience, mostly gained in the enclosure and in repair of dike breaks, together with progress of dredging and of auxiliary equipment plus a better knowledge of waves, permitted a bolder project: the Delta Project on which a start has been made recently. After completion, a second step may be made in the north by constructing dams through the gaps in the string of islands which is the actual coast of the North sea.

In many cases the last gaps have to be closed by floating a big concrete unit into place and sinking it. This may be a hazardous operation which can only be done in calm weather. In closing the last dike break after the 1953 flood a series of these operations had to be done in November, in the midst of the gale season. Our meteorologists found that there would be a calm period of sufficient length between two lows, crossing the Atlantic, Abraham and Charles, if the one between those two, Bernhard, would fade out. It did, and the operation was successful, but it was a great responsibility for our friends in the meteorological office in de Bilt.

These projects are multipurpose projects. They influence the economic life of whole regions and great care has to be taken that the result will be acceptable: the town and country planners are responsible for that.

The hydrologist is also involved, in several ways. Inside the enclosure dams, lakes come into being. After a few years the water in those lakes has been replaced by fresh water, which is used in time of drought in great areas around. Since 1937 the Yssel Lake, which is the former Zuider Zee, supplies fresh water to more than a million acres, where brackish water used to be plentiful, but where fresh water failed altogether.

The level of Yssel Lake has to be held to strict limits. It may not be so high that drainage of large areas would be effected; on the other hand there must be enough water for the needs. For the operation of the sluices in the enclosure, a fair knowlege of the future inflow is needed. Forecasting of rain is out of the question; fortunately most of the inflow comes from the Rhine.

The movement of flood waves down the Rhine is well known. The man in charge of the level of the lake knows several days in advance what he must expect and he tries to make room for an expected flood by evacuating as much water as possible. Long-term forecasting of the river flow is necessary in order to decide when to begin accumulating water for the summer months and to decide if rationing of water will be needed. (Up to now this has not been necessary.) In this respect we get great help from hydrologists of the Swiss Government, who use their snow surveys in forecasting river flow.

Part of the water of the Yssel Lake is used in pushing back the saltwater wedges in the rivers and canals. This will be possible on a greater scale after the Delta Project has been completed. Here we must try to achieve our aim using the minimum quantity of fresh water. A careful study of the phenomena in the transition zone between the fresh and the salt water is therefore in progress. We are here in another borderland: that between hydrology and hydraulic research.

I have not yet spoken of ground-water hydrology. I should mention two examples of this branch of hydrology; (1) the water supply for our cities, in the sand dunes along the coast, and (2) the circulation started by the reclamation of very low areas.

In the dunes the problem was originally determining the maximum amount of water that could be taken out, without upsetting the equilibrium between the fresh water bubble (Ghyben-Henzberg lens) and the sea water underneath. When it appeared that more would be needed, the problem arose how to replenish the stored amount by water from the rivers.

A very intensive hydrologic study, including boring of hundreds of observation wells, is being made of the underground flow towards the new polders of the Zuider Zee scheme. Marginal areas would suffer, if lakes which serve as buffer-zones were not conserved along the former coast. The levels of those lakes have to be adjusted to summer and to winter conditions in order to maintain satisfactory ground-water levels in the farm lands around the Zuider Zee.

A buffer lake will also be made between the areas yet to be reclaimed and Amsterdam. If this were not done, the ground-water table under that city would possibly be lowered to a level below the tops of the wooden piles on which it has been built. Consequently those piles would rot away. There is a nursery rhyme in the Netherlands:

> Amsterdam die grote stad
> Die is gebouwd op palen
> En als die stad eens ommeviel
> Wie zou dat dan detalen?

meaning:

> Amsterdam, that city big
> Has been built on piles
> And if the city would fall down
> Who then should pay for it?

If the hydrologists should make a capital error, it is evident that the *Zuiderzeewerken* would have to pay.

Ladies and Gentlemen, I hope you are convinced why a civil engineer in the Netherlands may be involved in geophysics. From the very start we realized that we could not do anything without international cooperation. That is why we are rather active in the IUGG and why we established so many contacts with the AGU. We consider your *Transactions* as the leading publication in this field and we are happy to have so many friends among your members.

I am proud to be the second Dutchman to receive the William Bowie Medal and I thank you with all my heart for the award.

Waterloopkundig Laboratorium, Raam 61, Delft,
The Netherlands

Tests of a New Submarine Gravity Meter*

F. N. SPIESS AND G. L. BROWN

Abstract—Comparisons of the LaCoste and Romberg submarine gravity meter with the Vening Meinesz pendulum gravity apparatus have been carried out on board USS *Tilefish* and USS *Baya*. Discrepancies between measurements made simultaneously with the two instruments show a root mean-square value of about three milligals, indicating that the gravity meter is an adequate replacement for the pendulum equipment with the added advantage of improved ease of obtaining numerical results at the conclusion of each observation.

Introduction—A recent paper [*Harrison, Brown*, and *Spiess*, 1957] has described the University of California Institute of Geophysics program of gravity measurements at sea during 1954 and 1955 using the Vening Meinesz pendulum apparatus. During this time the LaCoste and Romberg Company had under development a series of modifications of their standard spring-type gravity meter in order to adapt it for use in submarines. As their program neared completion it was possible to integrate the field testing of their equipment into the Institute of Geophysics work. In particular two series of tests were made, and are reported here. The first consisted in the reoccupation of pendulum stations made along the Pacific Coast. Discrepancies were not unreasonable, particularly in view of the inclusion of errors in navigation which could contribute to lack of agreement through differences in location and in Eötvös correction. The second tests were carried out on board USS *Baya* during a cruise from Hawaii to San Diego. In this case both the LaCoste and Romberg meter and the Vening Meinesz pendulums were operated simultaneously in order that the data could be compared before making the corrections for submarine depth and speed, and with knowledge that the observations were averaged over the same geographical location.

Equipment—The only apparatus previously in regular use for the measurement of gravity over the deep sea is the pendulum equipment of Vening Meinesz, operated in a submerged submarine. This equipment, then, can provide a check on the accuracy of other methods and also will set the standard of accuracy and ease of operation against which other methods must be judged. This equipment has been described by *Vening Meinesz* [1929, 1941] in two publications, and has remained unaltered since about 1938 by all users except for improvements in timing methods and in the auxiliary equipment [*Worzel* and *Ewing*, 1950, 1952; *Browne* and *Cooper*, 1950; *Cooper*, 1949]. The particular variants used in the work described here are discussed in detail by *Harrison, Brown*, and *Spiess* [1957].

The LaCoste and Romberg submarine gravity meter is shown in Figure 1. The basic sensing element is of the type of the LaCoste long-period seismograph [*LaCoste*, 1934, 1935], employing a carefully designed and constructed spring which has very close to linear response over a range of deflections corresponding to several thousand milligals change in acceleration. The sensing element is a null reading device; the point of attachment of the spring to the frame is altered by motion of a calibrated screw in order to return the meter beam to its zero position. A light transmission and photocell arrangement very similar to that used in the LaCoste and Romberg earth-tide gravity meters determines the direction and amount of deflection of the beam from its zero position, thus providing the signal for remote indication [*Clarkson* and *LaCoste*, 1957]. The beam position is indicated directly on a beam position microammeter and in an integrated form on a timing indicator microammeter.

The sensing element is mounted in a gimbal system which holds the element's orientation along the instantaneous apparent vertical. In order to provide a high degree of damping without increasing the static friction in the gimbals (as would occur if mechanical frictional damping were employed) an electrical servo system with the desired transient response is used. The result is that the instrument follows the apparent vertical closely, and the output of the sensing element is thus a measure of the magnitude of the vector sum of the force of gravity and the apparent force caused by the acceleration of the platform. The result of averaging such a reading, as was first pointed out by *Browne* [1937], is that a first-order

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* University of California, Institute of Geophysics Contribution Number 87

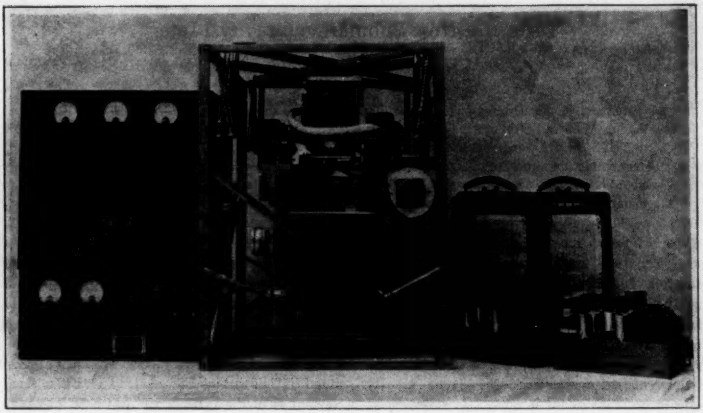

FIG. 1 - Submarine gravity meter

correction must be made for the net vertical acceleration (difference in vertical velocity) over the entire observation, and a second-order correction for the mean-square value of the horizontal acceleration over the averaging period. Long-period pendulums were devised by *Vening Meinesz* [1941] for use with the original pendulum equipment to provide information for computation of the second-order correction. A similar pair of long period pendulums is used in connection with the LaCoste and Romberg instrument for this purpose.

In contrast with the operation of the Vening Meinesz equipment, the apparent deflections of the two long-period pendulums in the LaCoste meter are measured electrically and fed continuously into a circuit which computes the second-order horizontal acceleration correction automatically. This computed correction is subtracted from the measuring screw reading by means of a differential gearbox to give a corrected gravity reading. The gravity reading can be changed by the operator, using a remote electrical control, and is continuously recorded in digital form by an Esterline Angus operational recorder using 16 binary digits. The gravity reading remains constant between alterations, but the measuring screw reading varies continuously during an observation at sea as the second-order correction changes. The effectiveness of this approach has been verified by laboratory tests in which the instrument was operated on a movable platform subject to horizontal accelerations having periodicity ranging from 7 to 15 sec and root mean-square (rms) amplitude ranging from 4000 mgal at short periods to 1200 mgal at the long periods (second order corrections of 8 mgal to 0.7 mgal). The resulting readings, including the second-order correction, were all within 0.5 mgal of the value obtained when the instrument was operated with no motion. The first-order correction was determined independently of both the pendulum and meter equipments using the depth recorder described by *Harrison*, *Brown*, and *Spiess* [1957].

Actual gravity measurements are made in a submerged submarine operating under reasonably stable conditions. Once the submarine is at the chosen depth the gimbals are freed and the gravity meter beam unclamped. The operator adjusts the gravity reading until the beam is very nearly in equilibrium, but so that its average position as shown on the timing indicator is moving slowly towards the null point. The Esterline Angus recorder is marked as the timing indicator passes through zero and, after several minutes, the gravity reading is again adjusted to make the timing indicator move towards zero. This procedure is repeated for about 30 min. The observed value of g is obtained by averaging the gravity reading shown on the Esterline Angus record, between the first and last times that the timing indicator crossed its zero position. This averaging only takes a few minutes so that g is obtained very shortly after the observation is completed. In the tests which are reported here the same averaging time (about 30 min) as that used with the pendulum equipment was employed; however, computations were made for smaller intervals within this period and these seemed to indicate that very often a satisfactory value could be obtained in as little as 15 min.

On the cruise on which they were operated simultaneously the meter and the pendulums were both located in the forward torpedo room, within 15 ft of one another. The pendulums were mounted about amidships with the plane of swing athwartships. The meter was slightly aft on the starboard side.

Sea tests—The first of the two test series reported here was conducted on board USS *Tilefish* in March 1955. Since these tests were the first at sea following extensive alterations and improvements on an earlier model, it was felt that the additional effort needed to install and operate both the LaCoste and Romberg and the pendulum equipments simultaneously would not be justified. Instead, several previously occupied gravity stations off the west coast of the United States were reoccupied (as closely as navigational accuracy would allow) for comparison purposes. The gravity meter counter readings were converted to milligals, corrected for instrument drift, submarine depth, and Eötvös effect, and compared with the international gravity formula values for the actual latitude of observation to give free-air anomalies. The calibration factor used was four parts in 1000 less than that determined by the manufacturer. This calibration is based on independent observations made by A. A. Day and J. C. Harrison with two later models of the LaCoste and Romberg submarine gravity meter. The measured differences of gravity between UCLA and the University of Washington at Seattle were compared with the differences established with Worden gravity meters.

The factors indicated for both meters were four parts in 1000 less than those supplied by the manufacturer. Base points for determining the actual values of *g* and the drift were 979,549.6 mgal at the Marine Physical Laboratory in San Diego and 980,738.9 mgal at the University of Washington in Seattle, the former determined by J. C. Harrison (private communication) and the latter by A. A. Day (private communication). The total drift for the cruise was +2.0 mgal. In Table 1 the free-air anomalies determined in this fashion are compared with the free-air anomalies at the corresponding nearby pendulum stations [*Harrison*, *Brown*, and *Spiess*, 1957]. No attempt was made to calculate the differences in topographic corrections which might arise from the slightly different locations of the meter and pendulum stations, thus these, as well as any navigational uncertainties, are included in the discrepancies listed. The resulting mean difference of 1.1 mgal and rms difference of 4.3 mgal are strongly controlled by a single station, no. 49, at which the difference is 11.4 mgals.

Results of the *Tilefish* tests were sufficiently good to encourage the execution of further, more elaborate tests. These became possible when Commander Submarines, Pacific Fleet, made USS *Baya* available for gravity work on a transit from Hawaii to San Diego in October of 1955. In addition to check observations at the Bishop Museum in Honolulu and at the Institute of Geophysics two groups of stations were made, each along a north-south line across the Murray Fracture zone, one at longitude 152°30′W and the other at 133°30′W.

TABLE 1 – *Comparisons of LaCoste and Romberg gravity meter values with previously occupied Vening Meinesz pendulum stations USS Tilefish, April 1955*

Number of nearby pendulum stations[a]	Free-air anomaly by pendulums	Free-air anomaly by gravity meter	Difference, pendulum − gravity meter value
	mgal	mgal	mgal
30	−27.9	−28.6	+0.7
31	−5.3	−8.7	+3.4
32	+9.0	+9.7	−0.7
33	−67.2	−67.4	+0.2
34	−61.3	−57.5	−3.8
35	−54.7	−58.6	+3.9
36	−0.4	−2.3	+1.9
37	−55.8	−57.3	+1.5
38	−30.2	−37.5	+7.3
39	−59.5	−58.7	−0.8
40A	−16.0	−11.4	−4.6
41	−7.8	−5.9	−1.9
42	−9.7	−7.0	−2.7
48	−18.2	−15.6	−2.6
49	−30.9	−42.3	+11.4
50	−40.0	−45.2	+5.2

Mean differences = +1.1 mgal; rms difference = 3.3 mgal.

Base values: Room 142, Marine Physical Laboratory, San Diego 979,549.6 mgal; Room 101, Johnson Hall, University of Washington 980,738.9 mgal; calibration factor 0.9960 × manufacturer's; drift +2.0 mgal.

[a] For position of pendulum stations, see *Harrison*, *Brown*, and *Spiess* [1957].

Table 2 – *Comparison of LaCoste and Romberg gravity meter values with Vening Meinesz pendulum values USS Baya October 1955*

Station no.[a]	Vening Meinesz pendulum value	LaCoste and Romberg gravity meter value	Pendulum value-gravity meter value
	mgal	mgal	mgal
Pearl Harbor			
Berth Sail #13	979,941.0	979,940.7	+0.3
98		980,094.5	
99	980,108.2	980,109.5	−1.3
100		980,170.8	
101	980,212.6	980,216.6	−4.0
102	980,243.2	980,249.9	−6.7
103	980,262.9	980,263.8	−0.9
104	980,277.1	980,278.6	−1.5
105	980,267.9	980,268.3	−0.4
106	980,286.4	980,284.9	+1.5
107	980,302.9	980,305.9	−3.0
108	980,366.3	980,368.0	−1.7
109	980,399.7	980,405.5	−5.8
110A	980,505.0	980,487.7	+17.3
110B	980,471.2	980,477.4	−6.2
123A	980,480.9	980,483.5	−2.6
123B	980,513.2	980,511.7	+1.5
124	980,520.0	980,518.2	+1.8

Mean difference = 1.9 mgal (exclusive of Station 110A); rms difference = 3.3 mgal.

Base for pendulum values: UCLA, Geology-Chemistry Building, Room 1275, 979,597.6 mgal.

Bases for gravity meter values: UCLA, Geology-Chemistry Building, Room 1275, 979,597.6 mgal, and Bishop Museum, Honolulu, 978,952.6 mgal.

Calibration factor 0.9960 × manufacturer's.

Gravity meter drift −1.8 mgal.

[a] For position of stations, see *Harrison*, *Brown*, *Spiess* [1957].

In this case again the calibration factor used was four parts in 1000 smaller than that of the manufacturer and the values 978,952.6 for Bishop Museum [*Bonini* and *Woollard*, 1957] and 979,597.6 for UCLA (J. C. Rose, private communication) were used as the gravity meter base stations, with a resulting −1.8 mgal drift being indicated. The observed gravity values, corrected neither to sea level nor for Eötvös effect, are listed for both the meter and the pendulums in Table 2. The rms value of the differences (excluding station 110A which will be discussed below) is 3.3 mgal.

During this trip, however, two sorts of difficulties were experienced and each of these will be discussed below.

The first difficulty was manifested only at stations 101 and 110A. At station 101 the gravity meter was in operation for about 25 minutes prior to the start of the pendulum observation. During the first 20 minutes of that time a consistent reading was obtained. Shortly after that a sudden drif of 17.4 mgal was observed. The gravity mete reading thereafter was steady and, during th pendulum observation, was as listed in Table where an error of −4 mgal is shown. At statio 110A a 17 mgal discrepancy between the two instruments is shown. In this case the major portio of the error must be ascribed to the gravity mete since stations 110A and 110B were run on heading east and west respectively in order to calibrat ship's speed through the water from the differenc in Eötvös effect. A similar reversed pair of station was made at 123A and 123B. The ship's spee calculated from the pendulums was realistic i both cases while that from the gravity meter wa in agreement at 123A-B but was out by a factor o 3 at 110A-B. When the gravity meter was returne to the factory, a corroded resistor was found nea an opening in the case, and shorting out thi resistor produced an 18-mgal change in reading. I thus seems reasonable to conclude that moistur on this resistor produced an intermittently erroneous reading, and a minor alteration in circuit layou has subsequently been made to eliminate possibl recurrence of this trouble.

The second difficulty was of a fundamentally different type, and was made apparent chiefly because a casualty in the air conditioning circulating water piping on the *Baya* forced her Commanding Officer to restrict operations to 200 ft submergence depth or less. At stations 111 through 122 a swell of 17- to 18-second period existed with acceleration amplitudes of 5000 to 9000 mgal as computed from long-period pendulum records. This particular gravity meter will not operate properly when subjected to vertical accelerations with amplitude greater than about 6000 mgal at a period of 10 sec, 4000 at 15 sec, or 3300 at 18 sec. As a result no readings were obtained at these 12 stations. If the full normal operating depth of the *Baya* could have been used, only one or two stations would have been lost. An examination of the pendulum records from the cruises reported by *Harrison*, *Brown*, and *Spiess* [1957] indicates that no more than five stations in 125 would have been lost if operating depths down to those normally available in submarines at present in operation by the U. S. Navy had been used. While these acceleration limits exist for the meter tested they have been greatly extended in later models.

Stations 98 and 100 are not listed because excessive vibration of the submarine led to very large middle pendulum amplitudes and the pendulum observations could not be reduced for these two stations. Gravity meter readings were obtained at these locations.

Conclusions—It is difficult to assess the meaning of the results of these two sets of observations unless some standard is available against which they can be judged. As far as the authors are aware, two sets of Vening Meinesz pendulums have never been operated simultaneously at sea, but data are available for successive observations made with a single equipment at one particular location. *Browne* and *Cooper* [1950] list ten stations at which double observations were made, although one observation of the pair was always taken at a shallow depth and was thus somewhat more disturbed than would normally be expected. In these cases the rms difference is 5.8 mgal if one difference of 25 mgal is rejected. A series of station reoccupations were made by *Browne* and *Cooper* [1952] using very careful navigating techniques for determining both position and Eötvös corrections. The result was an rms scatter from the mean of 1.4 mgal which should imply an rms difference between observation pairs of 2.0 mgal. A further idea of what can be expected may be drawn from the rms scatter of base swings made on surfaced submarines alongside various moorings. UCLA Institute of Geophysics stations alongside the U. S. Navy Electronics Laboratory pier at San Diego show an rms difference from the mean of 2.8 mgal for five observations. Nine base swings at Portland, England, give a 2.7 mgal difference from the mean [*Browne* and *Cooper*, 1952] while a scatter of swings at Gosport, Simonstown, and Trincomalee has an rms value of 2.2 mgal [*Girdler* and *Harrison*, 1957]. These would lead one to expect an rms deviation from the mean of 2.5 or 2.6 mgal and a consequent difference between pairs of observations having an rms value of 3.5 mgal, somewhat larger than the 3.3 mgal for the *Baya* operation.

On the basis of this comparison, then, the scatter between gravity meter and pendulum observations is of magnitude comparable with what one might expect between two sets of pendulum equipments. In the future, however, all possible opportunities should be utilized to install and operate pairs of gravity-determining devices simultaneously on the same submarine. Data from pairs of pendulum equipments as well as pairs of gravity meters and mixed pairs will be needed if a clear measure of consistency and agreement of these two types of apparatus is to be achieved.

Although these tests show no clear cut advantage in terms of equipment accuracy, and while the gravity meter replaces the mechanical and optical complexity of the multi-pendulum equipment with increased electrical complexity and there is no advantage for either in terms of space or weight, nevertheless the ease in operating and obtaining gravity values from the meter makes it an appealing competitor.

Acknowledgments—We are indebted to F. A. Vening Meinesz for making his pendulum equipment available to us for these tests, and to L. J. B. LaCoste for the use of the gravity meter and for lending a technician to assist in its operation at sea. J. C. Harrison provided much appreciated assistance and advice on the preparation of this paper.

Acknowledgment is also due to Commander Submarines, Pacific Fleet, and his staff and in particular to the officers and men of the USS *Tilefish* and USS *Baya* for their assistance in carrying out this operation. This work was supported by the U. S. Navy through Office of Naval Research Contract Nonr 233(19) and Bureau of Ships Contract NObsr 72512, NE 120221-4-5-6.

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The Use of Evenly Spaced Hemispheres to Evaluate Aerodynamic Forces on a Soil Surface

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Abstract—Direct and indirect measurements showed a substantial lift force on the surface roughness elements (such as soil grains resting on the surface) in a windstream. Lift was approximately four-fifths of drag on hemispherical roughness elements ranging from 0.16 to 5.08 cm in height. The ratio of lift to drag on the roughness elements of the surface remained essentially constant for any drag velocity of the fluid and any depth of the fluid boundary layer beyond a relatively shallow depth. The depth of the fluid boundary layer, on the other hand, had a profound influence on the magnitude of both lift and drag. This study throws new light on equilibrium conditions existing between soil grains and moving fluid at the threshold of movement of the grains.

A thorough understanding of the forces exerted on soil surfaces by wind is basic to the design of measures for coping with the wind erosion problem. It was desirable therefore to obtain some experimental data on the aerodynamic forces of drag and possible lift on roughness elements such as soil grains resting on the surface of the ground. This study was designed to give some information on the equilibrium conditions between the soil grains and the moving fluid at the threshold of movement of the grains. The study does not apply to forces operating on the grains during entrainment or motion.

Jeffreys [1929] suggested that fixed particles in a stream of water or air are subjected to lifting forces caused by specific pressure distributions on their surfaces. *Einstein* and *El-Samni* [1949, 1950] measured a significant lift force in a stream of water which tends to pull the natural sediment away from the surface. On the other hand, *White* [1940] concluded from an experiment with a wax grain tied to a cotton thread that the lift component of wind on a loosely packed bed of sand grains is negligibly small. The grain was prevented from moving downstream by the tension on the cotton which carried the horizontal force on the grain. The author of this paper believes that the grain could not rise perceptibly above the level of the surface even if lift was substantial, for if the grain were to rise somewhat, the force of wind higher up being many times stronger than either the forces of drag or lift at the surface would push the string with the attached grain down to an essentially horizontal position. An unattached grain or a grain attached to the loose end of the string facing upstream instead of downstream might have been lifted up as well as pushed forward.

Principles that govern lift and drag on a rough surface—According to the theory of Prandtl [*Brunt*, 1934] and *von Karman* [1934] for turbulent flow, the fluid velocity v at any height z above a rough surface over which no movement of surface material takes place can be expressed by

$$v_z = 5.75\ V_*\ \log_{10}\frac{z}{k} \tag{1}$$

where V_* is the so-called 'drag velocity' and k is the height at which the fluid velocity is zero (Fig. 1). The height k defines a theoretical surface and is constant for a given surface at all fluid velocities but varies with the height, shape, and arrangement of the roughness elements of the surface. V_* is equal to velocity at $30k/8.5$ and determines the slope of the velocity distribution curve when the velocity is plotted against the logarithm of height. The average drag τ_0 per unit of horizontal area of the entire surface may be computed from V_*, since $\tau_0 = qV_*^2$ where ρ is the density of the air, that is, the weight per unit volume of air divided by the acceleration due to gravity. The force τ_0 is dynamic acting in the direction of flow and composed of form drag and skin-fraction drag. No separation of the two forces is made in this study.

Since in turbulent flow pressure and drag vary as the square of velocity within the range of Reynolds number to which this study applies, it follows that pressure can be described with k as a linear scale for the size of the roughness elements. From this it was further concluded by *Einstein* and *El-Samni* [1949] that any convenient size of surface roughness element could be used to find the pressure distribution on its surface as long as it was sufficiently large to make the surface aerodynamically rough. It has been found by *Goldstein*

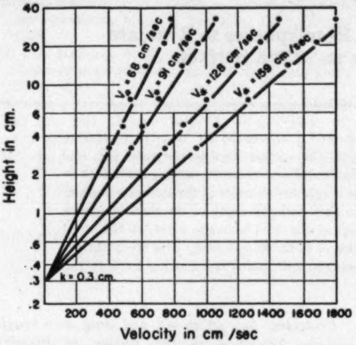

FIG. 1 – Wind velocity distributions above a fine gravel surface composed of hemispherical mounds 2.54 cm high and spaced in a hexagonal pattern three diameters (6 heights) apart.

[1938] that the critical Reynolds number $V_*r/\nu = 3.5$ distinguishes the condition under which the surface may be aerodynamically rough or smooth. In the above equation, r is the roughness (height of the particles on the surface) and ν is the kinematic viscosity of the fluid. In this investigation r is the radius of hemispherical roughness elements (Fig. 2) and ν is equal to 0.15 cm²/sec. The Reynolds number is dimensionless. If the value of the Reynolds number is smaller than 3.5, the topmost particles are submerged in a laminar sublayer to which the forces of turbulent flow do not apply. If, on the other hand, the Reynolds number is considerably greater than 3.5, the particles throw off eddies to their lee sides and disrupt the laminar layer. Of course, there is a transition state between the two flow conditions near the Reynolds number of 3.5.

Under a wind velocity equal to or greater than that required barely to move the soil particles, the particles disrupt the laminar layer if they are equal to or greater than 0.05 mm in diameter [*Chepil*, 1945]. It is significant to note that erodible soils always have a substantial proportion of particles greater than 0.05 mm. Therefore, soil movement is associated predominantly with turbulent flow of air against the particles. No upper limit can be given for the size of particles to which the forces of turbulent flow apply, but to make sure that the same effects of turbulent fluid flow apply to any size of particle greater than 0.05 mm, various sizes of surface roughness elements were used.

Procedure—A previously described wind tunnel [*Zingg* and *Chepil*, 1950] was used for measuring air velocity and the force of drag and lift on the roughness elements of the surface. An arrangement in which the air was forced through the upper-story room and recirculated to the fan was used. Pressure on the surface elements and velocity up to one foot above the average surface were measured under conditions of an expanding boundary layer at various distances downstream in the tunnel duct that was 56 ft long, 3 ft wide, and 3 ft high. At 50 ft downstream and halfway between the walls where most measurements were made, the fluid boundary layer was from 10 to 16 inches deep, depending on the height of the roughness elements of the surface. The depth of the fluid boundary layer is defined as the maximum height z to which (1) applies.

Velocity was recorded for different heights measured from the base of the roughness elements of the surface and plotted as shown in Figure 1. The theoretical surface k to which the straight-line velocity distribution curves projected ranged from $0.11r$ to $0.21r$ above the base of the roughness elements of height r, depending on the individual measurements.

The average drag τ_0 per unit of horizontal area of the entire surface was computed from V_* as already indicated. In addition, forces of average drag and lift on the roughness elements of the surface were determined directly from pressure distribution on the elements. In the initial measurements hemispheres 1.27, 2.54, and 5.08 cm high placed flat side down on the wind-tunnel floor were used as roughness elements. The pressure distribution was measured by means of a straight-tube alcohol manometer having an adjustable slope of zero to three degrees and reading to 0.0004-inch of water (Fig. 2). The positive-pressure end of the manometer was connected by rubber tubing leading through the tunnel floor and inside the hollow hemisphere to any of the nine taps (small holes) placed at various positions normal to the hemispherical surface. Starting at the base of the hemisphere, the taps were placed 30° apart along one line running parallel with and another running normal to the direction of the wind. The negative-pressure end of the manometer tube was connected similarly to a tap on top of the hemisphere. Thus, it was possible to detect and measure approximately the average lift and drag as resultant pressure

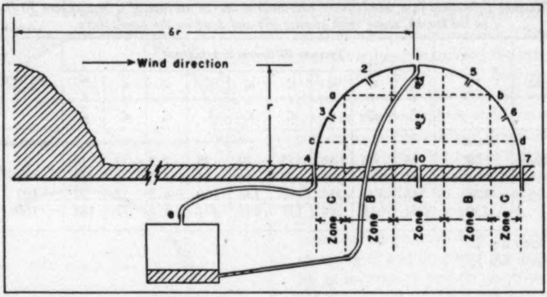

FIG. 2 – Diagrammatic representation of the method of determining pressure distribution on the hemispherica surface; for simplicity, pieces of rubber tubing connected to taps 2, 3, 5, 6, 7, 8, 9, and 10 running through the tunnel floor to be connected one at a time to the pressure end of the manometer at e, are not shown.

differences between the top and the bottom and the windward and the leeward parts of the hemisphere, respectively. Only one metal hemisphere was used to measure lift and drag while the remainder of the floor was covered with mounds of the same height and width as the hemisphere but composed of gravel 2 to 6.4 mm in diameter. It was impossible to make the mounds exactly hemispherical. These surface roughness elements were placed in a hexagonal pattern three diameters (six heights) apart. Thus, they occupied 0.11 of the total floor area. The remainder of the floor, including that around the metal hemisphere, was composed of the same gravel as that of the mounds.

The average drag per unit of horizontal area occupied by the hemisphere was taken directly as a pressure difference on the surfaces facing against and away from the wind. Let the cross-sectional areas normal to wind direction through the center of the spherical segments *ab*, *cd*, and 47 (Fig. 2) be equal to x, y, and z, respectively. The areas x, y, and z are equal to $\pi r^2\theta/360 - r^2 \sin \theta/2$ where the values of θ are the angles subtended by chords *ab*, *cd*, and 47, and r is the radius of the hemisphere. For any hemisphere, areas x, $y - x$, and $z - y$ occupy 0.183, 0.509, and 0.308, respectively, of the total cross-sectional area z. The average drag per unit of horizontal area occupied by the hemisphere therefore can be expressed approximately by

$$\tau = \frac{0.183(P_2 - P_5) + 0.509(P_3 - P_6) + 0.308(P_4 - P_7)}{2} \qquad (2)$$

where P_1, P_2, etc. are pressures at positions 1, 2, etc. as indicated in Figure 2.

The average lift per unit of horizontal area occupied by the hemisphere was determined from the average-pressure differences between the base of the hemisphere and zones A, B, and C (Fig. 2). The horizontal areas of zones A, B, and C were determined graphically to be equal to 0.062, 0.394, and 0.544 of the basal area of the hemisphere. If the average-pressure differences

$$P - P_A = \frac{(P_4 - P_1) + (P_{10} - P_1) + (P_{10} - P_1) + (P_7 - P_1)}{4}$$

$$P - P_B = \frac{(P_4 - P_2) + (P_{10} - P_8) + (P_{10} - P_8) + (P_7 - P_5)}{4}$$

and

$$P - P_C = \frac{(P_4 - P_3) + (P_{10} - P_9) + (P_{10} - P_9) + (P_7 - P_6)}{4}$$

where P is the average pressure at the base of the hemisphere and P_A, P_B, and P_C are average pressures at zones A, B, and C, respectively, then the average lift L per unit of horizontal area occupied by the hemisphere may be expressed approximately by

$$L = 0.062(P - P_A) + 0.394(P - P_B) + 0.544(P - P_C) \qquad (3)$$

Measurements were also made on gravel and wet sand mounds of the same shape and spacing

TABLE 1 – *Pressure differences in a windstream encountered on the surface of a hemisphere 50 ft downstream in the tunnel, along with average lift and drag on the hemisphere*

Roughness element	V_*	Pressure differences in dynes/cm²									Average drag[a]	Average lift[b]
		$P_2 - P_1$	$P_3 - P_1$	$P_4 - P_1$	$P_5 - P_1$	$P_6 - P_1$	$P_7 - P_1$	$P_8 - P_1$	$P_9 - P_1$	$P_{10} - P_1$		
	cm/sec										dynes/cm²	dynes/cm²
Metal hemisphere 2.54 cm high	68	28	90	81	15	22	28	−2.2	−11	14	27	19
	91	55	171	156	33	46	64	−1.1	0	40	48	37
	128	143	397	357	97	134	160	−4.3	13	97	102	79
	159	232	634	594	177	235	274	6.5	77	182	156	130

[a] Computed from Eq. 2.
[b] Computed from Eq. 3.

as the gravel mounds of the initial part of this study. The smallest wet sand mounds had a size equal to the largest soil particles commonly eroded by natural winds. Because the mounds were small, it was impossible to use the same method of determining lift and drag as on the hemispheres. Small hypodermic needles calibrated against a standard Pitot tube were used to measure pressure differences only between the top of the mounds (position 1, Fig. 2) and the base immediately to windward and leeward of the mounds (positions 4 and 7, respectively). The needles passing through the floor of the tunnel were imbedded in the sand or gravel in such a way that their openings were normal to and flush with the average surface. The pressure differences between positions 1, 4, and 7 were determined as in the initial study. The results with the hemispheres indicated that the pressure difference $P_4 - P_7$ represents twice the average drag per unit area on the hemisphere and the average of the pressure differences $(P_4 - P_1)$ and $(P_7 - P_1)$ is about 2.85 times the average lift per unit area on the hemisphere (Table 1). The forces of lift and drag on the mounds were taken therefore as pressure differences between the top and the bottom and the windward and the leeward positions, respectively, divided by these respective factors.

Two torsion balances accurate to five milligrams were used to measure directly the forces of lift and drag on a hemisphere suspended close to a horizontal surface in a windstream. As shown dia-

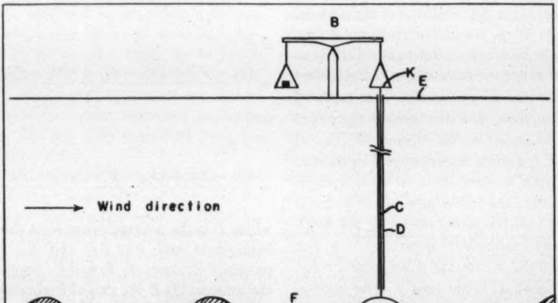

FIG. 3 – Diagrammatic sketch of apparatus for measuring drag and lift on a hemisphere.

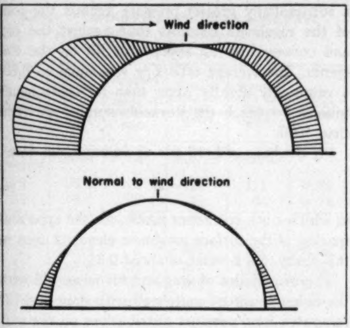

FIG. 4 – Pattern of pressure differences between position 1 on top of the hemisphere and any other position along the vertical axes parallel and normal to wind direction. Shaded areas above the circular line denote positive, and below the line negative pressure with respect to position 1; the length of lines in the shaded area denote the relative magnitudes of positive or negative pressure.

grammatically in Figure 3, hemisphere *A* was suspended from the end of the beam of balance *B* by string *C* leading through a vertical tube *D* through the tunnel ceiling *E*. One end of string *F* was connected to hemisphere *A* and led horizontally over pulley *G* and downward through the tunnel floor *H* through tube *I* to the end of the beam of balance *J*. The whole apparatus was placed approximately 54 ft downstream in the tunnel duct where, when the wind was turned on, the pressure inside the tunnel was approximately equal to the pressure outside. Consequently little or no air entered or escaped through tubes *D* and *I*. The surface on the tunnel floor was composed of gravel mounds of the same size and approximate shape as the hemisphere and arranged in the same pattern as in the initially described surfaces. The balances were leveled before the wind was turned on. After the wind was turned on, the balances again were leveled by placing appropriate weights on pans *K* and *L*. Lift on the hemisphere was registered on balance *B* by the decrease of tension on string *C* and drag was registered on balance *J* by an increase of tension on string *F*.

Lift and drag on hemispheres 3.18 cm high were determined at 3, 25, and 50 ft downwind in the tunnel duct. Measurements on all other roughness elements were made at 50 ft downwind.

Results—The pressure on the lower parts of the hemispheres was always found substantially higher than on a considerable area at and around the top. The pressure distribution (Fig. 4) was almost identical for nearly all sizes of hemispheres and wind velocities used. The actual magnitude of the pressure difference between different points on the hemisphere depended only upon the drag velocity of the fluid.

The ratio of lift to drag, L/τ was essentially constant for all sizes of hemispheres and drag velocities used except for two highest velocities on the largest hemisphere (Table 2). These latter cases had Reynolds numbers of the form $V_* r/\nu$

TABLE 2 – *Basic data on forces of lift and drag based on pressure measurements on evenly spaced hemispheres 50 ft downstream in the tunnel*

Roughness element	k	V_*	Reynolds number	Average drag on whole surface computed from V_*	Average drag on hemisphere	Average lift on hemisphere	Ratio of lift to drag on hemisphere
	cm	cm/sec		dynes/cm²	dynes/cm²	dynes/cm²	
Hemispheres 1.27 cm high	0.12	57	517	3.9	16	13	0.86
	0.12	79	715	7.5	28	22	0.78
	0.15	111	1007	14.8	55	42	0.75
	0.15	138	1254	23.0	91	83	0.91
Hemispheres 2.54 cm high	0.30	68	1232	5.5	27	19	0.71
	0.30	91	1651	10.5	48	37	0.77
	0.30	128	2317	19.6	102	79	0.78
	0.30	159	2885	30.4	156	130	0.83
Hemispheres 5.08 cm high	0.46	76	2772	7.0	41	33	0.80
	0.46	109	3962	14.4	96	88	0.91
	0.46	146	5298	25.6	142	165	1.16
	0.46	188	6840	42.7	217	287	1.32

Table 3 – *Average drag and lift based on pressure measurements on relatively small and evenly spaced sand and gravel mounds 50 ft downstream in the tunnel*

Roughness element	Reynolds number	Average drag on roughness element	Average lift on roughness element	Ratio of lift to drag
		dynes/cm^2	dynes/cm^2	
Wet sand mounds 0.16 cm high	47	2.6	2.2	0.84
	67	10.2	7.7	0.76
	93	16.0	13.3	0.83
	113	18.6	20.4	1.10
Wet sand mounds 0.32 cm high	124	3.0	2.3	0.77
	161	8.2	6.4	0.78
	216	14.2	14.2	1.00
	249	18.4	19.6	1.07
Gravel mounds 0.64 cm high	251	4.7	3.6	0.77
	342	15.8	11.4	0.72
	447	24.2	20.1	0.83
	557	44.5	36.8	0.83
Gravel mounds 1.27 cm high	506	7.8	6.2	0.78
	752	13.0	12.4	0.95
	989	18.6	20.4	1.10
	1197	32.9	31.6	0.96
Average	...	...	...	0.88

equal to 5298 and 6840. The average ratio of lift to drag for all other cases was 0.81. Repetition of the whole set of measurements of Table 2 produced essentially the same results as the first run of measurements.

The average drag on the hemispheres was from 4 to 6 times greater than the average drag computed from V_* for the whole surface. The ratio of drag on the hemispheres to drag on the whole surface increased slightly with the size of the hemispheres (Table 2).

The results with sand and gravel mounds, as shown in Table 3, again indicated that there was a substantially greater pressure against the foot of the roughness elements than against the top and consequently an appreciable lift on the elements. The average ratio L/τ was equal to 0.88, a value only slightly larger than for those hemispheres for which the Reynolds number was less than 5000.

Table 4 – *Concordance between average lift and drag measured with balances and computed from pressure distribution on the surface of a hemisphere 2.5 inches in diameter*

V_*	Drag		Lift	
	Measured	Computed	Measured	Computed
cm/sec	dynes/cm^2	dynes/cm^2	dynes/cm^2	dynes/cm^2
70	29	32	20	20
95	50	71	40	42
133	113	129	92	85
166	197	210	163	199

On the basis of both sets of experimental data

$$L = c\tau \tag{4}$$

in which c is a coefficient which, for the type and spacing of the surface roughness elements used in this study, has a value of about 0.85.

The magnitudes of drag and lift measured with the balances agreed quite well with drag and lift computed from pressure distributions on the surface of the hemispheres (Table 4). Since the computed values of drag are based on pressure results which measure form drag only, agreement tends to indicate that skin fraction drag is negligible in these cases.

The ratio of lift to drag was about the same at 25 and 50 ft downstream in the tunnel where the expanding fluid boundary layer was approximately 27 and 40 cm deep for hemispherical roughness elements 3.18 cm high (Table 5). The ratio of lift to drag appeared to be somewhat higher at three feet downstream in the tunnel duct than at 25 and 50 ft. The depth of the fluid boundary layer at three ft was only about 5 cm. It is evident from these results that increasing the depth of the fluid boundary layer, after a certain limit of depth has been reached, has little influence on the ratio of lift to drag. However, the depth of the fluid boundary layer had a profound influence on the magnitude of both lift and drag.

Discussion—Einstein and *El-Samni* [1949] used an equation of the form

$$\Delta p = C_L\,(\rho/2)\,u^2 \tag{5}$$

in which Δp is the pressure difference between the top and the bottom of the hemisphere and which was assumed to be the lift force on the hemisphere, and u is the fluid velocity at 0.35 hemisphere diameters away from the theoretical wall represented by height k in these experiments. Eq. (5) is applicable to a surface composed of closely packed hemispheres. Since from the experiments reported in this paper it was found that the ratio L/τ on the roughness elements of the surface remains virtually constant for any size of roughness element and drag velocity within the des-

TABLE 5 – *Average drag and lift on hemispheres 3.18 cm high at different positions in the tunnel*

Position in tunnel	V_* at 50 ft downwind	Approximate depth of fluid boundary	Average drag on hemisphere	Average lift on hemisphere	Ratio, lift to drag
feet downwind	cm/sec	cm	dynes/cm²	dynes/cm²	
3	95.2	5	128	117	0.91
25	95.2	27	86	64	0.74
50	95.2	40	80	62	0.77
3	165.8	5	300	282	0.94
25	165.8	27	287	229	0.80
50	165.8	40	258	200	0.77

TABLE 6 – *Values of lift coefficient C_L for a surface composed of closely packed hemispheres*

Roughness	V_*	τ_0	Presumed L_A	u at 0.35 D	C_L based on u at 0.35 D
	cm/sec	dynes/cm²	dynes/cm²	cm/sec	
Hemispheres 1.27 cm high	57	3.9	3.3	295	0.063
	79	7.5	6.4	414	0.062
	111	14.8	12.6	514	0.079
	138	23.0	19.6	637	0.079
Hemispheres 2.54 cm high	68	5.5	4.7	331	0.071
	91	10.5	8.9	443	0.076
	128	19.6	16.7	615	0.074
	159	30.4	25.9	773	0.072
Hemispheres 5.08 cm high	76	7.0	6.0	413	0.058
	109	14.4	12.3	592	0.059
	146	25.6	21.8	794	0.058
	188	42.7	36.4	961	0.066
Average	...	...	...	...	0.068

ignated range of the Reynolds number, it may be expected that the ratio of lift L_A to drag τ_0 per unit area of surface composed of closely packed hemispheres would remain constant too. If this assumption is true, lift on the closely packed hemispheres would be approximately equal to $0.85\tau_0$. On the basis of this assumption, values of L_A based on this study were substituted for those of Δp of (5) which gave an average value of C_L equal to 0.068 (Table 6) as compared with 0.178 found by *Einstein* and *El-Samni* for water. However, this discrepancy is due principally to the method of determining lift on the hemisphere. In experiments by Einstein and El-Samni, lift on the hemisphere was taken as a pressure difference between the top and bottom of the hemisphere. In these experiments, lift was computed from the pressure distribution on the hemisphere. Furthermore, from these experiments it was found that the pressure difference between the top and the bottom of the hemisphere is about 2.85 times the lift on the hemisphere. If this factor is correct, the value of C_L based on determinations by *Einstein* and *El-Samni* [1949] should be $0.178/2.85 = 0.0624$, a value only slightly smaller than the value of C_L based on these experiments. The slight discrepancy easily may be due to the differences that existed between the two studies with respect to the relative distance between the hemispheres. In the study by Einstein and El-Samni the hemispheres were closely packed; in this study they were three diameters apart. This distance was chosen to imitate the average distance that was found between sand grains removable from surfaces of loose sand beds [*Zingg*, 1952].

Conclusion—This study shows that lift on hemispherical surface projections, similar to soil grains resting on a surface in a windstream, is substantial. Therefore, lift must be recognized together with drag in determining an equilibrium or critical condition between the soil grains and the moving fluid at the threshold of movement of the grains. The ratio of lift to drag on the roughness elements of the surface remains essentially constant for any drag velocity of the fluid and any depth of the fluid boundary layer beyond a relatively shallow depth.

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Probability Distributions of Water-Wave Slopes under Conditions of Short Fetch

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Abstract—Slope probability distributions were measured for a fetch of about 15 inches, using a small wind tunnel containing a water boundary. For this very short fetch, the mean-square slope was found to be higher than previous longer-fetch data for wind velocities greater than about 10 kn. At 18 kn the short-fetch mean-square slope was 70 pct higher.

Evidence of peakedness of the slope distributions was found in the short-fetch data. The mean value of the distributions was measured to reach a maximum in the downwind direction and was about 1.5° in the region of 18 kn.

Introduction—Probability distributions of slopes of wind-disturbed water surfaces for various wind velocities have been reported by *Cox* and *Munk* [1954] and by *Schooley* [1954]. The results are in reasonable agreement in the direction of the wind for wind speeds between 5 and 25 kn, even though different methods of measurement were used and the locale of the measurements was the Pacific Ocean in the first case and the Anacostia River (a tidal estuary in the District of Columbia) in the other. The fetch in the Anacostia River was about 1000 ft, which is probably several orders of magnitude less than the fetch in the Pacific. Since the fetches in the two cases were widely different, the agreement in slope distributions implies that the fetch is of secondary importance, at least for fetches greater than 1000 ft. It is the purpose of this paper to compare the measurements of slope probability distributions for an average fetch of about 15 inches with the previous longer-fetch data.

Experimental equipment—The small wind tunnel, the lower portion of which is occupied by water, previously described by *Schooley* [1955] and shown in Figure 1, was used to gather the experimental data. The total fetch, determined by the length of the lucite wind channel, was 26 inches. Wave profiles for the various wind velocities were recorded by taking 0.001-sec flash pictures focused on the front lucite-water-air intersection. Full scale enlargements were made, and the slope of the water surface was determined graphically at 0.5-cm intervals near the central portion of the pictures for a total distance of about 25 cm. At the higher wind velocities the limits of measurements were made to correspond to approximately an integral number of the longest wave length present. The average fetch in the region of measurement was about 15 inches. Figure 2 shows one of the wave-profile pictures, retouched to make the lucite-water-air boundary visible in the small illustration.

Analysis of data—The slope measurements for each wind velocity were grouped into five-degree interval histograms, and from these data cumulative frequency of occurrence points were calculated and smoothed ogive curves drawn [*Kenney*, 1947]. Points taken from the ogive curves were then replotted on linear probability paper for the various wind velocities considered. The plot for 20 kn is shown in Figure 3. Deviation of the linear probability paper plot from a straight line shows that the actual distribution is peaked because the curve has a detectable amount of sigmoid curvature. The flaring out of the actual distribution curve from a straight line in the upwind direction indicates that the distribution is skewed in the downwind direction, confirming the findings of *Cox* and *Munk* [1954]. (In this paper the slopes looking upwind are negative and those downwind are positive, which is reversed from the convention used by Cox and Munk.)

In Figure 3 the straight line representing the gaussian approximation of the actual distribution is drawn through the 16 pct and 84 pct points, which define the plus and minus standard deviation (σ) points of the gaussian approximation. The standard deviation of the gaussian approximation is considered to be one half the difference between the 16 pct and 84 pct points, and the mean-square slope is the square of the tangent of the standard deviation angle.

The mean-square slopes for the various wind velocities studied are shown in graphical form by the upper curve in Figure 4, where the mean-square slope is the ordinate and the wind velocity is the abscissa. Also shown are points taken from the relatively long-fetch results referred to previously. It is evident that for wind velocities above about 10 kn, the mean-square slope for the short-fetch waves was measured to be considerably greater than for the waves formed by longer fetches. At 18 kn it is about 70 pct higher. This interesting

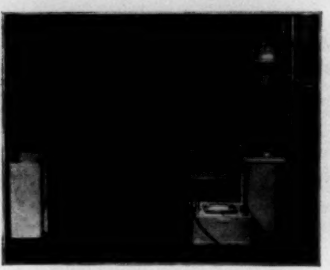

FIG. 1 – Wind tunnel with a water boundary

result may be due to the sheltering of part of the surface from the wind by the higher, longer-fetch waves, thus decreasing the amount of short-fetch waves which are the principal contributors to the magnitude of the mean-square slope.

The curved line in Figure 3 shows the smoothed cumulative frequency of occurrence for the actual distribution, which in this case is both skewed and peaked compared to a gaussian distribution. Thus it is desirable to determine the median, mean, and mode values for the actual distribution. The median slope can be determined directly from the point where the actual distribution curve crosses the 50 pct ordinate. The mean-slope value represents the distance between the zero-slope line and the center of gravity of the original histogram (not shown). Using the mean and median values, the mode may be calculated by the approximate method given by Kenney. Table 1 shows the mean, median, and mode values for the various wind velocities studied. The last column of Table 1 was based on the appearance of the actual distribution curves of the cumulative frequency of occurrence plots for the various wind velocities. A pronounced sigmoid shape was accepted as evidence that the actual distribution was peaked compared to a gaussian distribution. All the actual distributions showed evidence of peakedness except for 16 and 22 kn. Thus there is an inconclusive hint that perhaps the peakedness may become less with increased wind velocity under the conditions that the data were taken.

The functions of Table 1 are all positive, except the means at the two lowest wind velocities. This result indicates that the distributions are mostly skewed in the downwind direction. It is also evident that all three functions reach a maximum in the region between 16 and 20 kn. This would indicate that the slope distribution goes through a region of maximum non-gaussian shape and then becomes more nearly gaussian again as the wind velocity increases. In this general region it becomes evident that water droplets are starting to be drawn into the air near the water surface. It may be possible that this phenomenon may tend to make the slope distributions more nearly gaussian for the higher wind velocities. It is also interesting to note that this is the same region of wind velocities as that in which *Mandelbaum* [1956] found evidence of a critical wind velocity for air-sea boundary processes.

Figure 5 is included to show the actual wave slope distribution for a 20-kn wind together with two gaussian approximation distributions having the same areas under the curves. The general shapes of the solid and the dotted curves are very similar to the one presented by Cox and Munk when it is remembered that the negative-positive wave-slope convention is reversed. The dashed curve in Figure 5 was included to show that the gaussian approximation fits the actual distribution better if it is centered around the mode rather than the zero-slope line in this particular case.

Sources of error—Several things have contributed errors in the data. The probe for the air velocity meter was about two inches from the water sur-

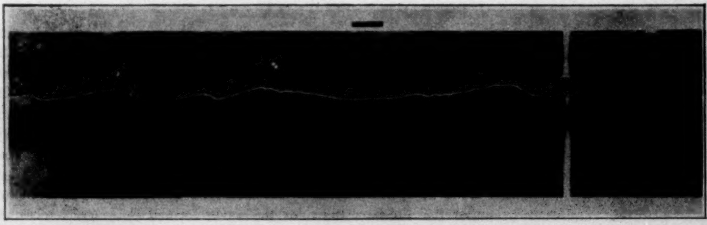

FIG. 2 – Wave profile with 16 kn wind

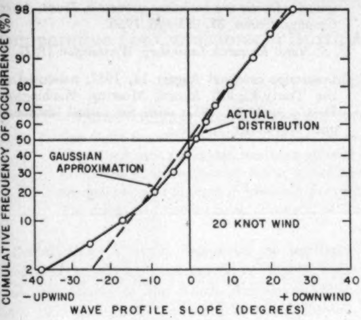

FIG. 3 - Linear probability paper plot

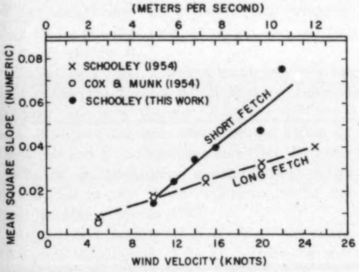

FIG. 4 - Mean square slope vs. wind velocity

face, and at the higher wind velocities there was a tendency for its calibration to be affected by water spray. Care was taken to check the accuracy of the instrument against two other instruments in an air stream outside the wind tunnel. Experimental errors caused by imperfect wave absorption at the end of the channel are also probably present. The difficulty of obtaining good absorption increases as the wind velocity is increased. Limited experiments were made for optimizing the slope of the screen beach to reduce reflection. Other less successful absorbers were also tried.

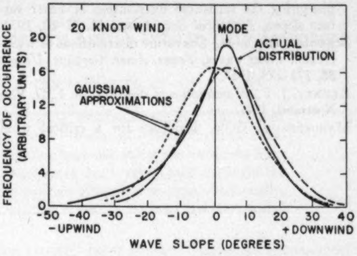

FIG. 5 - Wave slope distribution curves

TABLE 1 - *Mean, median, and mode of actual distributions for various wind velocities*

Knots	Degrees slope			Distribution peaked
Wind velocity	Mean	Median	Mode	
10	−1.0	0.2	2.6	Yes
12	−0.1	2.5	7.7	Yes
14	0.4	1.9	4.9	Yes
16	1.2	4.0	9.6	No
20	1.1	2.2	4.4	Yes
22	0.6	1.5	3.3	No

The accuracy of the lucite-water-air intersection as representative of the water surface contour is not known quantitatively. Inspection of the pictures indicates that it is fairly satisfactory as a first approximation. In experiments of this kind there is concern as to whether the statistical samples are large enough and are representative. The sampling used was based principally on the desire to get a reasonable amount of results in reasonable time. Even so, the original wave-profile pictures were taken in 1953. It is regretted that photographic difficulties made the picture for 18 kn unusable, and hence there is a gap in the data at a very interesting point.

Conclusions—Under the conditions in which the data were taken and analyzed it may be concluded that for 15-inch fetch water waves:

(1) The mean-square slope is greater than for fetches of more than 1000 ft. At 16-kn wind velocity the mean-square slope is 70 pct greater.

(2) The actual distributions of wave slope for various wind velocities appear to be peaked and to be skewed in the downwind direction.

(3) The amount of peakedness and skewness reached a maximum in the region between 16 and 20 kn.

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Comparative Ice Conditions in North American Arctic, 1953 to 1955, Inclusive

JOHN J. SCHULE, JR., AND WALTER I. WITTMANN

Abstract—Regularly and systematically conducted aerial reconnaissance is at the present time replacing ship and shore observation as the primary means of collecting sea-ice data. Since 1953 new knowledge has been gleaned concerning seasonal variations occurring deep within the outer confines of North American pack-ice areas. Ice breakup and disintegration are now believed to begin in icebound, far northerly regions. These regions expand seasonally. The origin and development of several of these 'centers of sea-ice removal' are discussed.

Introduction—A rapid expansion of regularly scheduled aerial ice reconnaissance flights over seas and oceans of the North American Arctic since 1953 has added immeasurably to our knowledge and understanding of ice conditions there. In addition, it has provided additional knowledge of and insight into the environmental processes that are the result of ice distribution and, in some cases, determine it.

Except for a brief, intensive excursion into the field during the Second World War by German military scientists [*German Hydrographic Institute*, 1950] and for brief and sporadic flights by Canadian and U. S. agencies since that time, virtually no comprehensive understanding of ice distribution in the North American Arctic has been possible prior to 1953.

As described recently [*U. S. Hydrographic Office*, 1956], the ice program of the U. S. Navy Hydrographic Office became firmly established in 1953. The result has been a much more synoptic and inclusive understanding of daily, weekly, monthly, and annual variations of ice conditions within Arctic sea areas than had previously been possible. Through comprehensive aerial ice reconnaissance and the use of standardized ice observational procedures, extensive knowledge can now be gleaned of periodic variations of sea ice conditions such as boundaries between ice and water, concentrations within the ice, age and thickness of the ice, the degree of ice deformation, and the stage of ice disintegration.

Data, of course, are still insufficient for the determination of an accurate and complete concept of 'normal' ice conditions, such as might be necessary for a complete revision of a publication such as H.O. Pub. No. 550 [*U. S. Hydrographic Office*, 1946a]. However, several important new concepts have emerged from the data acquired in the three years 1953 to 1955. Several historical notions derived as a result of older ice information, gained largely through sporadic and widely scattered ship ice reports, have proven themselves inconsistent with the newly obtained information. This new information, and not the older concepts, will form the basis for the following discussion.

Types of ice and ice packs—Figure 1 depicts the probable average maximum extent of sea ice throughout the entire year (slant hatching). Most of this ice is commonly known as 'polar ice,' or ice which survives the short thawing season each year and in some cases may be the source region for hard and heavily ridged and hummocked ice that drifts southward. On the other hand, a quite different type of ice is that characteristically present in the Baffin Bay-Labrador Sea area, in the southwestern Canadian archipelago and in the Bering Sea. It forms and is completely disintegrated within a single season. Such ice is commonly called 'winter ice,' or ice of one year's growth, and is most prevalent in the areas represented by the dotted hatching in Figure 1.

Furthermore, two types of Arctic ice pack must be distinguished. The first is a stream of mobile ice drifting southward to its eventual destruction; the second may be thought of as a quasi-stationary pack or one more or less confined to its region of origin throughout its life span.

The East Greenland coastal ice is the most dramatic of the drift-stream type. Its minimum coverage extends to the vicinity of Scoresby Sund or approximately 70°N, in October. Its maximum extent occurs in June. At this time it is in the form of a continuous drift having its origin in a trajectory across the entire Arctic Ocean over the north geographical pole, from whence it moves southward to Kap Farvel, rounding the cape and continuing northwestward to approximately 61°N. This ice stream has been found to be characterized by an extremely marked short-term variation in extent and concentration. Indeed, central portions of the stream are sometimes entirely cut off, owing to variation in the wind-induced components of current and ice drift. At times within the naviga-

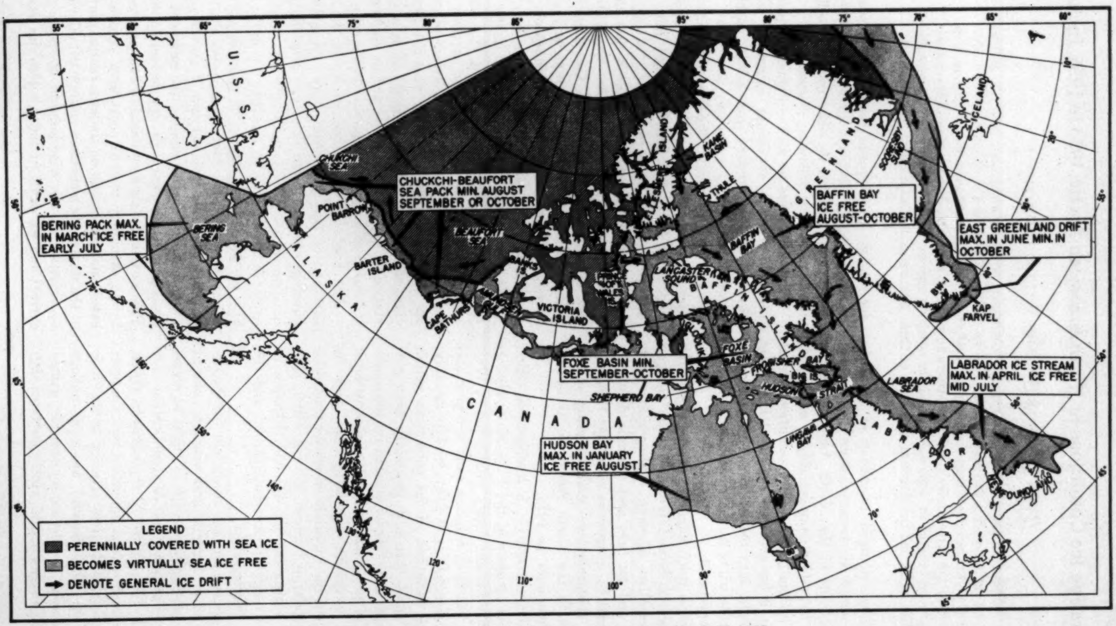
U. S. S. R.
CHUKCHI SEA
BERING SEA
BERING PACK MAX. IN MARCH ICE FREE EARLY JULY
CHUCKCHI-BEAUFORT SEA PACK MIN. AUGUST SEPTEMBER OR OCTOBER
POINT BARROW
BEAUFORT SEA
BARTER ISLAND
ALASKA
CAPE BATHURST
BANKS IS.
PRINCE OF WALES IS.
VICTORIA ISLAND
ELLESMERE ISLAND
KANE BASIN
THULE
LANCASTER SOUND
BAFFIN BAY
BAFFIN ISLAND
BAFFIN BAY ICE FREE AUGUST-OCTOBER
GREENLAND
SCORESBY SUND
ICELAND
EAST GREENLAND DRIFT MAX. IN JUNE MIN. IN OCTOBER
BW-1
KAP FARVEL
IGLOOLIK
FOXE BASIN
FOXE BASIN MIN. SEPTEMBER-OCTOBER
FROBISHER BAY
BIG IS.
HUDSON STRAIT
SHEPHERD BAY
CANADA
HUDSON BAY MAX. IN JANUARY ICE FREE AUGUST
UNGAVA BAY
LABRADOR
LABRADOR SEA
LABRADOR ICE STREAM MAX. IN APRIL ICE FREE MID JULY
NEWFOUNDLAND
55°
60°
65°
70°
75°
80°
85°
10°
20°
30°
40°
50°
60°
70°
90°
100°
110°
120°
130°
140°
150°
160°
170°
180°
LEGEND
PERENNIALLY COVERED WITH SEA ICE
BECOMES VIRTUALLY SEA ICE FREE
DENOTE GENERAL ICE DRIFT

FIG. 1 – Seasonal expansion in the coverage of sea ice, 1953–1955

tion season, for example, ships may close the coast at ports in the vicinity of the 65th parallel, whereas obstreperous ice is, at the same time, raising havoc with shipping attempting to reach the USAF base, situated at BW-1, much farther southward at approximately 60°N.

A unique characteristic of the East Greenland coastal ice is its complex composition. In the period between June and October and in the region between Iceland and the southern tip of Greenland, three primary types of ice occur. Most prevalent is polar ice of several seasons' growth that is being transported southward to its eventual destruction. Considerable quantities of winter ice formed to the north are also included. Along the immediate coastline, a great deal of fast ice formed in the inland fiords is supplied by the strong and frequent foehn winds, blowing eastward off the Greenland ice cap.

The Baffin Bay pack is an example of the type largely confined to its region of formation, and contrary to prior belief [*Weaver*, 1951], it begins to form in late October or early November. It attains total coverage by approximately January 15 and has totally melted by approximately August 15. Although conditions vary greatly during the navigable season, the new data indicate that more mobile ice containing greater quantities of ridged and hummocked ice and to a lesser extent old hard polar floes are more predominant on the Baffin Island side then elsewhere. The historical notion of the 'middle pack' [*U. S. Hydrographic Office*, 1946a] seems doubtful. The last ice to disintegrate is apparently not the ice of the central bay but the ice moving southward along the western shores of Baffin Bay. This ice is partly of polar origin, containing floes from the Kane Basin and Lancaster Sound source regions.

The Labrador ice stream, although considerably less formidable in thickness and inaccessibility to shipping, contains quantities of sea ice contributed from both the Baffin Island coast and, late in the season, from Ungava Bay and Hudson Strait. Along the Labrador coast especially it has been found that persistent ice and 'severe' ice seasons are the result much more of environmental conditions in the source regions to the north than of those over the area in the immediate vicinity of the ports and harbors affected. Ice drift here, however, is also extremely responsive to such local factors as storms, currents, and winds. Coastal harbors here have an extremely serious ice problem owing to the effects of these factors in combination with tidal forces and bathymetry. As a result, marked diurnal variations sometimes occur in the case of accessibility to harbors along the northeastern coast of Labrador.

In any of the areas shown in Figure 1, it has been noted that a severe June is frequently followed by a mild or light July. Exactly the converse is often true, as was especially evident in the approaches to Frobisher Bay during the 1953 ice season.

In Foxe Basin the notion of a self-contained cyclonic ice circulation held by such pioneering explorers as Bob Bartlett, [*U. S. Hydrographic Office*, 1946b] is believed on the basis of more recent information to be only partially true. The cyclonic circulation seems to prevail only in the northern portion of the Basin. It is believed that in the southern portion of Foxe Basin much of the ice sets southward and southeastward, affecting the clearing of ice from Hudson Strait.

In 1955, excellent comprehensive reconnaissance data indicated that by late September only a minute quantity (approximately 3 pct) of the ice survived the season in Foxe Basin and was available for later classification as polar ice. The predominant polar ice historically attributed to this region is probably present only in unusual years. Rather, persistence of ice in this region appears to be more the result of the interaction of extreme and radical variations in the direction of wind stress on the ice, shallow bathymetry, and an almost completely surrounding coastline. These factors create in Foxe Basin the most severely ridged and hummocked ice found throughout the polar regions of North America, except for the regions just to the north of Greenland and Ellesmere Island. Another erroneous notion sometimes evident in Arctic literature is that the ice in the northern part of Foxe Basin is more concentrated and persistent than that in the central or southern portions. The converse has definitely been observed during the seasons here reported.

In the water area between Amundsen Gulf and Shepherd Bay, total ice coverage is attained by late November, and it is believed that in most seasons the ice is completely disintegrated in the period between August 15 and September 15. Exceptions to this rule occur in persistent strings of remnant pressure ridges found in the eastern portions of this region. Here, as in other areas discussed, extreme variability occurs both within the season and regionally as a result of drift situations induced by storms, winds, and other environmental factors. Particularly at both extremities of the region, early clearing in the navigation season may lead to unjustifiable complacency, as when heavy ice forced its way southward through Victoria Strait (to the southeast of Victoria Island) in August 1955, and also when the polar pack intruded upon the coast between Barter Island and Cape Bathurst during early September 1953.

Understanding of ice conditions deep within the polar pack between the meridians of the Bering Sea and Cape Bathurst is at this time incomplete. This is true not only because of the sparse environmental data which exist over the oceanic area north of the Alaskan coast, but equally because of the wide spacing in the network of meteorological stations fringing that area. However, every year the additional scientific information gained from ice reconnaissance and drifting ice stations makes the potential of accurate forecasting here even greater than in the more complicated, shallow, and enclosed areas previously described. The new data, for example, indicate that the line depicting the probable minimum ice coverage in the North American Arctic (heavy dotted line in Fig. 1) dips deeply southward into the Canadian Archipelago between Prince of Wales and Victoria Islands. Ice measurements made at the Canadian-U. S. Joint Weather Stations since their establishment in the period 1946–1949 agree with the aerial reconnaissance data in placing this line farther south than either Russian ice charts [*U.S.S.R.*, 1953] or the *Ice Atlas of the Northern Hemisphere* [*U. S. Hydrographic Office*, 1946a] would lead one to believe. Both atlases indicate the polar ice line as lying entirely seaward of the Greenland-Canadian Archipelago.

The Bering-Chukchi pack ice attains its maximum coverage in early March and is usually totally open in early July. Although somewhat lighter, it closely resembles the pack ice of Baffin Bay in that a quasi-stationary ice mass exists which disintegrates largely in situ.

Certain scientific approaches concerning the ability to predict within-season variability in pack ice conditions are becoming possible as a result of comprehensive ice reconnaissance. Predominant among these is a more accurate determination of the relationship between the velocity of ice drift and wind velocities. In addition, the relationships that exist between varying combinations of environmental parameters are becoming better known. Some of these relationships are the amount of ice disintegration and pressure ice that occurs through an 'ice season,' the thinning out or consolidation of pack ice that occurs owing to the components of vorticity of the wind stress on the ice, and the effect of these factors on incipient ice destruction or disintegration. Work on this later problem is proceeding at the present time. Especially significant is the work started at the Hydrographic Office in relating the local time-rate of change of ice concentration to the vorticity of the wind stress, to the advection of ice, and to the change in ice concentration that results from melting or freezing.

Annual variability in the Arctic pack ice—Perhaps the most spectacular information gleaned through ice reconnaissance during the past three years has concerned the extreme variations in ice distribution that occur from one season to the next. Figure 2 clearly illustrates this point. In 1955 during the navigation season in mid-July the Baffin pack was entirely confined to the Baffin Island area, and its extension in the Labrador ice stream extended farther south than was the case in the previous two seasons. The Thule approaches in the region of 75°N at the same time were completely devoid of ice, unlike the previous two years. Although initial convoys into Thule sighted no sea ice in 1955, at the same time in 1954 two heavy Wind-class icebreakers were battling difficult ice conditions in bringing the first ship into Thule. These facts clearly indicate the danger of generalizing, from individual ship experiences, on the severity of the ice season over a wide area. Scientific correlations based on ice charts compiled from sporadic ship reports are therefore of extremely doubtful validity. Ships supplying the Labrador coast in 1955, for example, would have reported a severe ice year for the entire eastern Arctic. Ships similarly supporting Thule would have reported the converse.

The same dramatic differences in year-to-year ice conditions are evident in Figure 3, on the Alaskan side. In 1954 icebreakers were able to circumnavigate Banks Island, with little difficulty. In both 1953 and 1955, on the other hand, ice conditions in this same area were extremely difficult, and a similar operation was inconceivable. In 1953 the difficulties in early September were largely confined to the eastern portions of the north Alaskan coast, whereas in 1955 persistent on-shore drift and mass movement of the polar pack were much more obvious in the western portions of the area. Early indications for conditions such as those encountered in 1954 were reflected in computations of theoretical ice drift made for the formative ice development period from Sep-

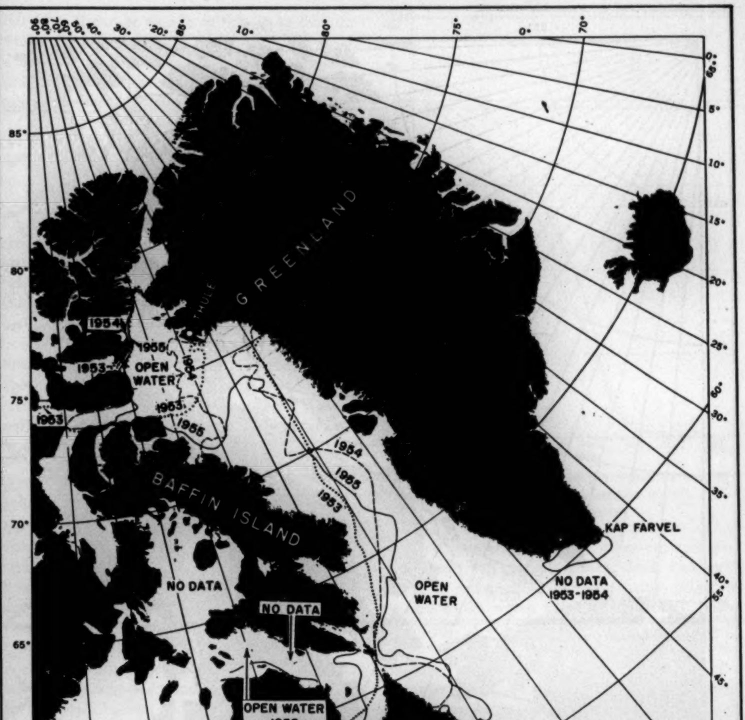
GREENLAND
THULE
1954
1955
1953
OPEN WATER
1953
1955
1953
1954
1955
1953
BAFFIN ISLAND
NO DATA
NO DATA
OPEN WATER
KAP FARVEL
NO DATA 1953-1954
OPEN WATER 1955
1955
1954
1953
85°
80°
75°
70°
65°
60°
55°
95°
90°
85°
80°
75°
70°
65°
60°
55°
0°
5°
10°
15°
20°
25°
30°
35°
40°
45°
50°

FIG. 2 – Annual variation of pack ice boundaries in mid-July in the eastern North American Arctic

tember 1953 to April 1954. Theoretical drift during this period reflected an extremely strong, east-to-west movement of 2½ to 3½ nautical mi/day. The extreme southern portion of the Arctic pack at this time was characterized by increasing ice drift velocities from east to west in the region north of Point Barrow, naturally reflecting a thinning out or divergence of the polar ice. The ensuing light ice experienced west of Banks Island and the extreme northerly position of the ice

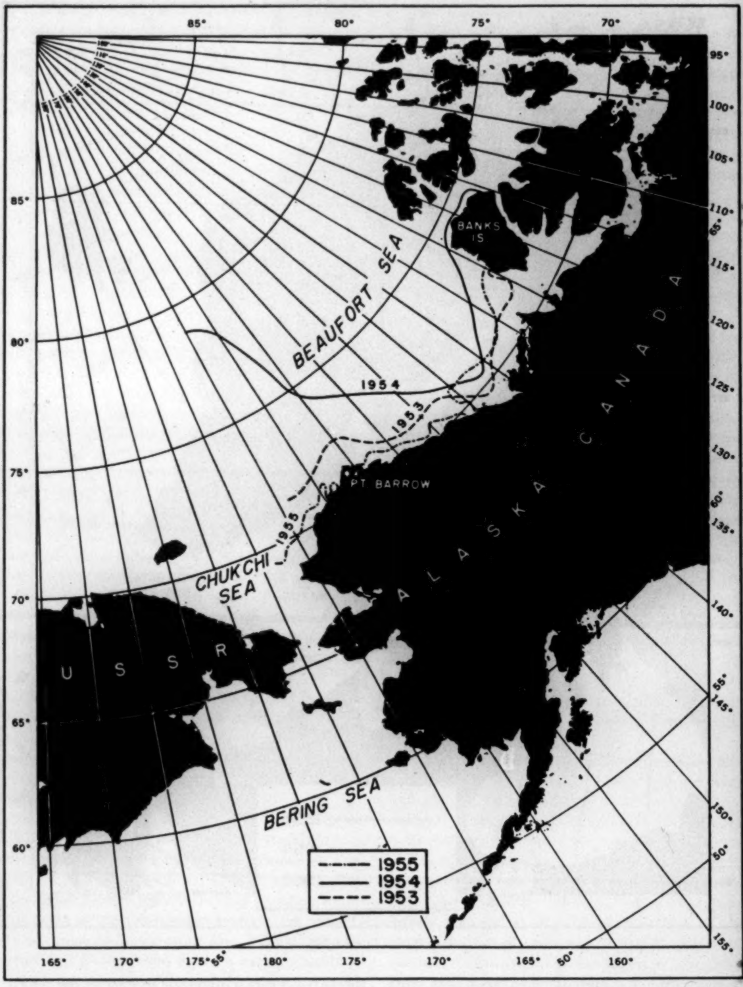
BEAUFORT SEA
BANKS IS.
1954
1953
1955
PT. BARROW
CHUKCHI SEA
ALASKA
CANADA
U S S R
BERING SEA
1955
1954
1953
85°
80°
75°
70°
65°
60°
95°
100°
105°
110°
115°
120°
125°
130°
135°
140°
145°
150°
155°
165°
170°
175°
180°
175°
170°
165°
160°
55°
50°

Fig. 3 – Annual variation of the polar pack boundary in early September along the north Alaskan coastline

boundary off Point Barrow (Fig. 3), were probably in large part determined by the anomalous drift situation described.

Figure 4, showing the area of ice present in the Baffin Bay-Davis Strait area for the breakup period of 1953–1956, emphasizes that internal differences of ice distribution are most responsible for an ensuing light or heavy ice year in a particular area. It can be seen from this figure that the total production of ice in each year, 1953–1955, is approximately constant; yet the great annual and areal differences in navigable conditions already described occurred despite this constancy.

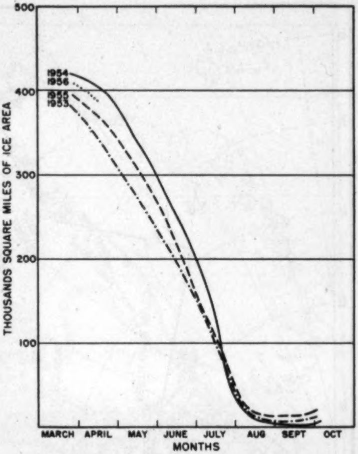

FIG. 4 – Seasonal expansion in the estimated quantity of ice in the North American Arctic, 1953–1956, inclusive

Centers of sea-ice removal and disintegration—Perhaps the most important contribution of ice reconnaissance to sea-ice forecasting is the significant additional knowledge gained of certain peculiar areas of weakness within the pack ice. Figure 5 depicts six regions where open, partially open, or very unstable ice predominates, despite air temperatures in these regions having averaged below −25°F for two or three months prior to their existence. Disintegration and removal of ice proceed outward from these areas during the breakup season. A few of the areas will be discussed briefly in the paragraphs below. Schematic charts showing the general seasonal expansion of these centers of sea removal for the Eastern and Western portions of the North American Arctic are shown in Figures 6 and 7, respectively.

The North Open Water is probably the most classical of these regions. Its existence has been known for hundreds of years, and it was exploited by the whaling expeditions of the 17th through the 19th centuries. The older explanation for this occurrence has been the sinking of the West Greenland Current as it crosses the submerged ridge across Davis Strait following along the coast of Greenland, and its reappearance, with consequent upwelling, as it rises again along the ridge of northern Smith Sound [*Killerich*, 1933]. Recent information suggests a more credible explanation to be a back-logging and jamming of ice moving generally southward across the geographic bottleneck of northern Smith Sound. Persistent, frequent, and strong northerly winds jam the ice in this area, causing separation and continuous removal of ice south of the jam. Each year at the culmination of the Arctic winter, in early March, the line of polar ice across the northern sound is very clearly in evidence curving northward in an architectural form similar to a naturally built stone or steel arch bridge. For the past three years the extent of this North Open Water has for the first time been accurately surveyed throughout the navigation season.

The ice jamming and strong wind factors are probably also largely responsible for the Barrow Strait Polynya and the Igloolik Lead. The Big Island Lead, on the other hand, is more attributable to natural current divergence combined with persistent, strong off-shore winds. The Bathurst Polynya apparently has still other explanations: here strong rip currents flowing back and forth across a submerged ridge apparently result in vertical eddies which keep the water well mixed and supply a constant replacement of relatively warm surface water. A further explanation for the Bathurst Polynya is the probable existence of a permanent southwesterly setting current across the western entrance of Amundsen Gulf. Open water and unstable ice result as the current continuously removes ice from the consolidated ice cover of inner Amundsen Gulf.

The Chukchi Lead is probably the result of a surface reappearance of the Bering Sea Current, which flows weakly through Bering Strait to the northward. It widens or narrows markedly, however, with changes in the offshore and onshore components of ice drift.

The centers located in the eastern North American Arctic make their first appearance in late March (Fig. 6). At this time the North Open Water is defined at its northward limit by the boundary between the polar ice northward of Smith Sound, to the westward by the fast frozen ice of Jones and Lancaster Sounds, to the eastward by the fast bay ice of the coastal indentations of western Greenland, and to the south by the solid pack ice cover of Baffin Bay. In addition to

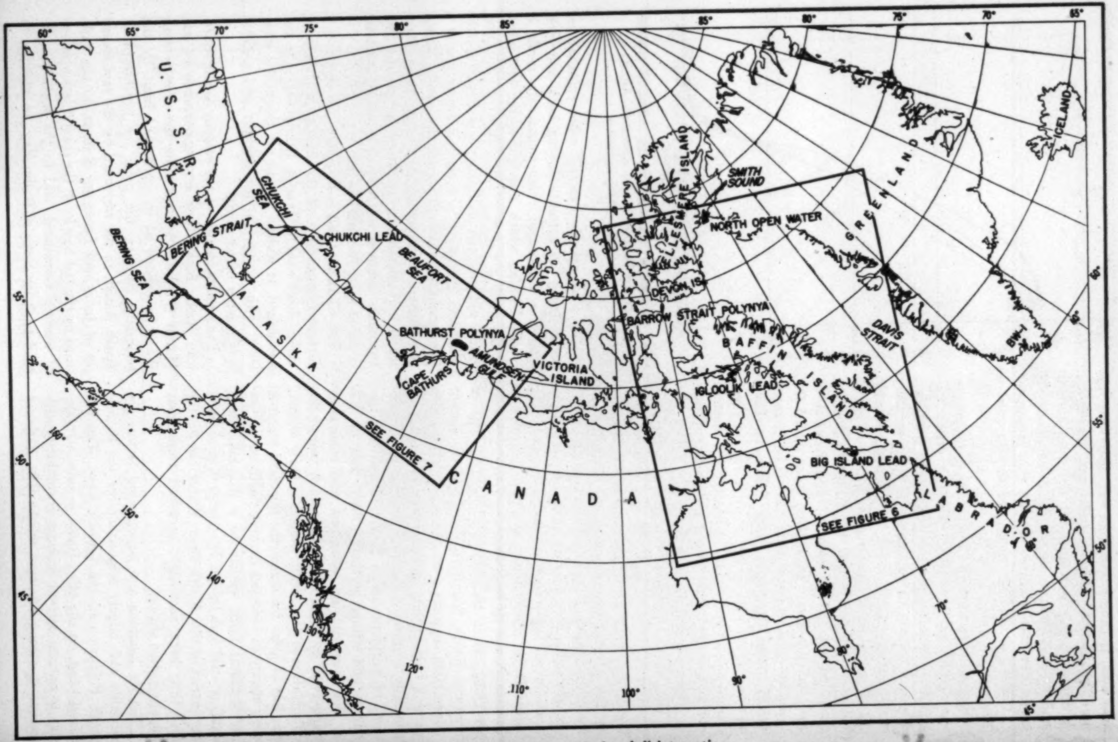
U. S. S. R.
BERING SEA
BERING STRAIT
CHUKCHI SEA
CHUKCHI LEAD
BEAUFORT SEA
ALASKA
BATHURST POLYNYA
CAPE BATHURST
AMUNDSEN GULF
VICTORIA ISLAND
SEE FIGURE 7
CANADA
ELLESMERE ISLAND
SMITH SOUND
NORTH OPEN WATER
DEVON IS.
BARROW STRAIT POLYNYA
BAFFIN ISLAND
IGLOOLIK LEAD
BIG ISLAND LEAD
SEE FIGURE 6
DAVIS STRAIT
GREENLAND
ICELAND
LABRADOR
60°
65°
70°
75°
80°
85°
90°
100°
110°
120°
130°
140°
150°
160°
55°
50°
45°

FIG. 5 – Centers of sea ice removal and disintegration

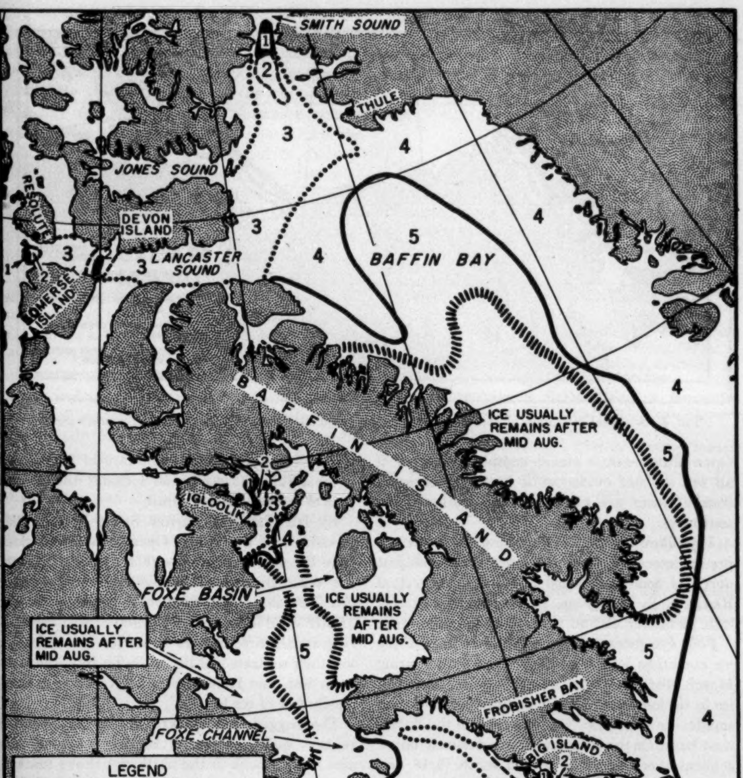
SMITH SOUND
THULE
JONES SOUND
RESOLUTE
DEVON ISLAND
LANCASTER SOUND
SOMERSET ISLAND
BAFFIN BAY
BAFFIN ISLAND
ICE USUALLY REMAINS AFTER MID AUG.
IGLOOLIK
FOXE BASIN
ICE USUALLY REMAINS AFTER MID AUG.
ICE USUALLY REMAINS AFTER MID AUG.
FOXE CHANNEL
FROBISHER BAY
BIG ISLAND
HUDSON STRAIT
LEGEND
SLUSH, YOUNG ICE AND/OR OPEN WATER IN LATE MARCH
EXPANSION INTO OPEN WATER AREA BY MID MAY
EXPANSION OF OPEN WATER BY MID JUNE
EXPANSION OF OPEN WATER BY MID JULY
EXPANSION OF OPEN WATER AREA BY MID AUGUST

FIG. 6 – Seasonal expansion of centers of sea ice removal in the North American Arctic: eastern portion

the approximately 300 sq mi of open water usually evident in the March reconnaissance, large portions of northern Baffin Bay east of Devon Island generally contain predominantly young ice or ice probably not more than a week old, in spite of a theoretical ice potential in this region at this time of considerably greater than four feet [*Lee* and *Simpson*, 1954]. By mid-June the same North

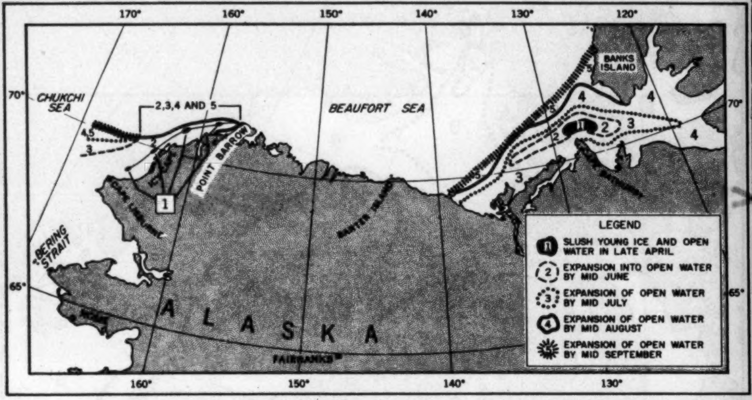
170°
160°
150°
140°
130°
120°
70°
65°
CHUKCHI SEA
BEAUFORT SEA
2,3,4 AND 5
POINT BARROW
CAPE LISBURNE
BARTER ISLAND
CAPE BATHURST
BANKS ISLAND
BERING STRAIT
NOME
FAIRBANKS
ALASKA
1
2
3
4
4,5
5
LEGEND
SLUSH YOUNG ICE AND OPEN WATER IN LATE APRIL
EXPANSION INTO OPEN WATER BY MID JUNE
EXPANSION OF OPEN WATER BY MID JULY
EXPANSION OF OPEN WATER BY MID AUGUST
EXPANSION OF OPEN WATER BY MID SEPTEMBER

FIG. 7 – Seasonal expansion of centers of sea ice removal in the North American Arctic: western portion

Open Water area is almost completely devoid of all sea ice, and evidences of breakup and lesser concentrations are present to the southeast and southwest.

The Barrow Strait Polynya in late March is pre-evidenced by two broken ice areas, one just north of Somerset Island and one just west of Resolute. By mid-June, it has spread eastward into Lancaster Sound, and is completely open.

Poor flying weather precluded knowledge of the ice conditions in the northern Foxe Basin during March 1955. However, an 8/10 concentration of ice in the form of small and medium floes and even smaller ice size types was observed in the northwest basin. On the other hand, progressively larger concentrations occurred to the south (9/10 and 10/10). By mid-June definite openings were evident in the vicinity of Igloolik. One of the authors, accompanying the initial ice reconnaissance flight over the area, personally observed in March of 1956 an 18- by 100-mi area containing only such unstable ice types as windrowed slush and young ice in the northwestern extremities of Foxe Basin. This area persisted in spite of low surface air temperatures in sharp contrast to the virtually solid, heavily hummocked ice over the entire remaining portion of the Basin southward of Foxe Channel.

In mid-March the Big Island Lead (Fig. 6) usually exists as a narrow coastal strip stretching southeastward from that island. Less than 1/10 ice cover characterizes the lead. By mid-June a rapid widening develops southward of Big Island; by mid-July the expansion includes the greater part of central Hudson Strait.

By late July the Barrow Strait Polynya has merged with the North Open Water and both have become contiguous with the open waters of the West Greenland Current and the Labrador Sea. The Big Island Lead now encompasses the greater central portion of Hudson Strait. By mid-August, all three centers of sea ice removal have lost their separate identity as Baffin Bay, the Labrador Sea, and Hudson Strait have become completely free of sea ice.

The rugged, hummocked ice in Foxe Basin behaves quite differently. In late July only the area near Igloolik in the northwest shows marked diminution in ice cover. Not until after mid-July does the area of less than 1/10 ice cover spread rapidly to the south and southeastward. Toward late September the Basin experiences its seasonal ice minimum, despite the fact that new ice occasionally starts or has already started to form. It should be stressed that aerial reconnaissance throughout the Arctic has emphasized the wide overlap, four to six weeks or more, between the last stages of the disintegration process and the time of widespread new ice formation.

The expansion of open water from areas deep within the Arctic pack ice is just as spectacular in the western portion of the North American Arctic (Fig. 7) as it is in the eastern. The Bathurst Polynya, south of Banks Island, shows a continuous expansion after late April, especially ~~in the~~ mid-June through mid-August period. The Chukchi Lead, too, shows continuous expansion, although in the Point Barrow vicinity congestion frequently occurs throughout the period from mid-July to mid-September. Worsening in this manner occurs as the more mobile pack ice of the late summer can and does respond to the predominant direction of ice drift in any particular period under consideration. Strong southerly and southwesterly sets in the ice drift during August 1955 resulted in the difficult ice season experienced.

All composite seasonal ice charts compiled at the Hydrographic Office since 1953 support the arguments of ice breakup occurring outward from the centers of sea ice disintegration. Also, the new data for 1956 reveal all the centers mentioned as areas of thinner and less concentrated ice.

Conclusion—In just a few years, comparative study of aerial ice reconnaissance information has greatly increased our knowledge of ice distribution in the North American Arctic. Such data strongly indicate that annual variability in ice distribution and the location of ice boundaries is probably due in large part to year-to-year variations in the drift and movement of ice rather than to variations in the quantity of ice produced. Within each season, too, considerable variability occurs in ice coverage, following a complex but usually recurring pattern. The primary feature of ice disintegration in the Arctic is not an orderly and gradual northward recession of pack boundaries during the summer months, but rather a steady outward progression from several well defined areas of weakness in the various sea ice regions.

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Time of Flow Studies, Ottawa River, Lima, Ohio

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Abstract—Chemical (sodium chloride), colorimetric (fluorescein dye), and radioactive (rubidium^{86}) tracer techniques were used to measure the time of flow of the Ottawa River below Lima, Ohio. Two runs were made during a two-week period in August 1956, when low stream conditions prevailed. In the first run fluorescein dye and rubidium tracer were introduced into the stream and measured at two stations located 1.0 and 1.9 miles downstream, and in the second, dye and radioactive tracers, and sodium chloride were introduced and measured at three stations located 1.0, 1.9, and 4.5 miles downstream. The results show that under existing test conditions all tracers gave similar results and the maximum deviation was generally less than ten per cent. The equipment and facilities needed to carry out the field and laboratory tests are described and the costs and limitations of each method are indicated.

The use of radioactive tracers for determining flow time and dispersion in water courses has been known to hydraulic and sanitary engineers for some time. *Joly* [1922] proposed the use of radium for this purpose, and suggested an acid pitchblende solution (containing radium) be introduced into a stream and that the evolved radon be measured by an electroscope. *Hess* [1943] reported the use of radium as a tracer for flow measurements in tank experiments. A variety of reactor-produced radioisotopes have been used in hydraulic studies in the last decade and include sodium^{24} [*Karrer* and others, 1946; *Knop*, 1951; *Putnam* and *Jefferson*, 1956], potassium^{42} *Seaman* [1956], iodine^{131} [*Archibald*, 1950; *Thomas* and *Archibald*, 1952; *Straub* and *Hagee*, 1957; *Tsivoglou* and others, 1956], phosphorus^{32} [*Parker*, 1955; *Thomas*, 1956ab], bromine^{82} [*Straub* and *Hagee*, 1957; *Sons*, 1952; *Montens*, 1952, 1955], rubidium^{86} [*Straub* and *Hagee*, 1957; *Fox*, 1952; *Ambrose* and others, 1957; *Truesdale*, 1953], cobalt^{60} [*Anonymous*, 1953], scandium^{46} [*Putnam* and *Jefferson*, 1956; *Ely*, 1957], radium [*Bullen*, 1954a], and radon [*Bullen*, 1954b]. These isotopes were used to determine flow time and dispersion in pipes, settling basins, detention tanks, natural lakes and ponds, oxidation ponds, and ground waters.

In the past engineers have relied upon salt and dye tracers for an evaluation of flow time and dispersion, or have depended upon the use of floats or cross sectioning. These methods have certain drawbacks, and the use of radioisotopes offers some hope for a better method of determining these parameters.

In connection with studies that were being carried out by the Robert A. Taft Sanitary Engineering Center on the behavior of oils in the Ottawa River near Lima, Ohio, information was desired on the time of travel of the effluents from an activated sludge sewage treatment plant and a refinery. To obtain this information, time of flow studies were carried out using chemical (sodium chloride), colorimetric (fluorescein dye), and radioactive (rubidium^{86}) tracer techniques. Two runs were made during a two-week period in August, 1956, under low stream flow conditions.

Field operations—For the first run, 1.5 lb of fluorescein dye and 265 millicuries (mc) of rubidium^{86} tracer were added to the Ottawa River at the sewage treatment plant outfall. At each of two stations, located 1.0 (Sta. A) and 1.9 (Sta. B) miles below the point of introduction of the tracers, one-quart samples were collected at the mid and quarter points of the stream. Duplicate 100-ml portions were taken for laboratory counting and for determination of the fluorescein concentration. The temperature of the residual sample was recorded and the activity level was measured on a survey meter (Model MX5 survey meter, Beckman Instrument Co., Richmond, California) and a field scaler unit (Model 80 Field Scaler, Berkeley Division, Beckman Instrument Co., Richmond, California), each of which was equipped with a rubber-encased G-M probe. A notation was also made as to whether the dye concentration was higher or lower than that of the preceding sample.

In the second run, made a week later, the amount of fluorescein was increased to six pounds, since weak color and erratic results had been obtained in the initial run. The dye, along with 300 mc of rubidium^{86}, was added at the sewage treatment plant outfall. At a point approximately 0.1 mile upstream, 3000 lb of sodium chloride were also released.

Since the field scaler measurements gave useful data in the first run this unit was selected to give a continuous record of the activity levels (integrated) passing Station A. Unfortunately, the instrument failed just at the time that activity reached this station. Samples were collected as in Run 1, but no field measurements were made, all samples being analyzed in the laboratory. Because of the increased concentration it was possible to follow the dye for a greater distance and samples were collected at a third station (Sta. C) located approximately 4.5 miles below the sewage treatment plant outfall. Visual observation showed good dye color in the river the following day at a station 7.8 miles below the point of introduction.

Laboratory measurements—For the determination of radioactivity a sample of 10 ml was placed in an aluminum dish, evaporated to dryness, and counted in an internal proportional counter (Model PC-1, Nuclear Measurements Corp., Indianapolis, Indiana.).

The fluorescein dye concentration was estimated on a Beckman Model B spectrophotometer, from the absorbance of fluorescein at a wave length of 490 millimicrons (mμ) in a 5-cm cell. The refinery waste materials had negligible absorbance at this wave length while fluorescein absorbance was high. Measurements of the dye by fluorescence was not possible because of the variable fluorescence of the refinery effluent. Settled samples were read against a blank of Ottawa River water taken prior to the arrival of the dye. Fluorescein, in concentrations of 40 to 1000 μg/l, gave absorbance readings ranging from 0.05 to 0.70 with a reproducibility of five per cent.

The Mohr method was used to estimate chloride concentrations [*American Public Health Assn.*, 1955]. Settled river-water samples were titrated after pH adjustments only. Sample volume varied from 25 to 100 ml depending on chloride levels. The titration error was relatively independent of sample size, hence high concentrations were subject to more absolute error. Reproducibility in titration of duplicate samples was within 0.3 mg, hence the variation on a 100-ml sample was less than 3 mg/l; on a 25-ml sample 12 mg/l. The presence of a slight oily film on the river precluded the use of a conductance cell for chloride estimation. The refinery and petrochemical plant cooperated in holding salt brine discharges from process operation to minimal amounts to avoid rapid fluctuations in river chlorides during the sampling period.

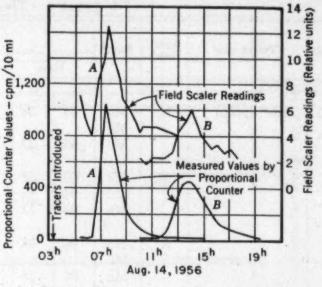

FIG. 1 – Ottawa River, time of flow using radioactive rubidium tracer; first run, August 14, 1956

Results—The results obtained in the first run were plotted as indicated in Figure 1 and summarized in Table 1. With a stream flow of approximately 23 – 26 cfs, the modal time of travel for the mid-stream samples was 3.97 hr from the sewage treatment plant outfall to Station A (1.0 mi downstream) and 10.38 hr to Station B (1.9 mi downstream) based on laboratory radioactivity measurements; 4.13 hr and 10.63 hr, respectively, based on field radioactivity data. The mean flow times (laboratory data) to Stations A and B amounted to 4.53 hr and 10.93 hr, respectively. Data obtained with the field survey meter or with the dye tracer were unsatisfactory.

The results of the second run (stream flow approximately 19 – 21 cfs) are plotted in Figure 2 and summarized in Table 1. On the basis of the mid-stream sample data, the modal times of travel to Stations A, B, and C were 4.25 hr, 10.25 hr, and 21.5 hr using rubidium^{86}; 4.0 hr, 9.7 hr, and 21.5 hr using fluorescein; and 5.3 hr, 10.9 hr, and 22.0 hr using sodium chloride, respectively. The sodium chloride was introduced 0.1 mi upstream of the other two tracers and the time required for it to reach the downstream stations would therefore be expected to be somewhat greater than is the case for the other tracers. Float studies for this 0.1-mile section indicated a median and mean range time of 35 min. The mean values are listed in Table 1 along with modal and median values.

The results with the various tracers may be compared through a consideration of the time required to flow from Station A to Station B, Station A to C, and Station B to C. From an examination of the data in Table 1, it will be seen that the midstream modal value for time of travel be-

TABLE 1 – *Time of flow between stations*

Run	Tracer used	Location[a]	Value[b]	Time interval[c]											
				T_{O-A}		T_{O-B}		T_{O-C}		T_{A-B}		T_{A-C}		T_{B-C}	
				h	m	h	m	h	m	h	m	h	m	h	m
1	Rb^{86} (prop)	L	Mo	04	08	10	23	...	...	06	15	...	...	...	...
			Md	...	...	...	...	...	...	...	...	...	...	...	...
			Mn	04	33	10	48	...	...	06	15	...	...	...	...
		M	Mo	03	58	10	23	...	...	06	25	...	...	...	...
			Md	04	22	10	47	...	...	06	25	...	...	...	...
			Mn	04	32	10	56	...	...	06	24	...	...	...	...
		R	Mo	04	08	10	23	...	...	06	15	...	...	...	...
			Md	...	...	...	...	...	...	...	...	...	...	...	...
			Mn	04	28	10	48	...	...	06	20	...	...	...	...
	Rb^{86} (scaler)			04	08	10	38	...	...	06	30	...	...	...	...
2	Rb^{86}	L	Mo	04	15	10	10	...	...	05	55	...	...	...	...
			Md	...	...	...	...	...	...	...	...	...	...	...	...
			Mn	04	40	10	30	...	...	05	50	...	...	...	...
		M	Mo	04	15	10	15	21	30	06	00	17	15	11	15
			Md	04	35	10	25	21	45	05	50	17	10	11	20
			Mn	04	35	10	25	21	52	05	50	17	17	11	27
		R	Mo	04	15	10	10	...	...	05	55	...	...	...	...
			Md	...	...	...	...	...	...	...	...	...	...	...	...
			Mn	04	40	10	30	...	...	05	50	...	...	...	...
	Dye	L	Mo	04	18	10	09	...	...	05	51	...	...	...	...
			Md	...	...	...	...	...	...	...	...	...	...	...	...
			Mn	04	35	10	20	...	...	05	45	...	...	...	...
		M	Mo	04	00	09	42	21	30	05	42	17	30	11	48
			Md	...	...	...	...	...	...	...	...	...	...	...	...
			Mn	04	30	10	12	21	24	05	42	16	54	11	12
		R	Mo	04	24	10	12	...	...	05	48	...	...	...	...
			Md	...	...	...	...	...	...	...	...	...	...	...	...
			Mn	04	35	10	20	...	...	05	45	...	...	...	...
	Salt	L	Mo	05	24	11	00	...	...	05	36	...	...	...	...
			Md	...	...	...	...	...	...	...	...	...	...	...	...
			Mn	05	30	10	58	...	...	05	28	...	...	...	...
		M	Mo	05	18	10	54	22	00	05	36	16	42	11	06
			Md	...	...	...	...	...	...	...	...	...	...	...	...
			Mn	05	34	11	00	22	17	05	26	16	43	11	17
		R	Mo	05	24	10	35	...	...	05	11	...	...	...	...
			Md	...	...	...	...	...	...	...	...	...	...	...	...
			Mn	05	39	11	05	...	...	05	26	...	...	...	...

[a] L, left bank; M, midstream; R, right bank.

[b] Mo, mode; Md, median; Mn, mean.

[c] T_{O-A}, T_{O-B}, etc., time interval required for flow from point of introduction to Station A, point of introduction to Station B, etc.

tween these stations amounted to 6.0, 17.25, and 11.25 hr with rubidium[86]; 5.7, 17.5, and 11.8 hr with fluorescein; and 5.4, 16.7, and 11.1 hr with sodium chloride, respectively. The elapsed time based on the mean values did not differ greatly from the modal values.

In Table 2, the deviations based upon the midstream modal and mean values are shown, and

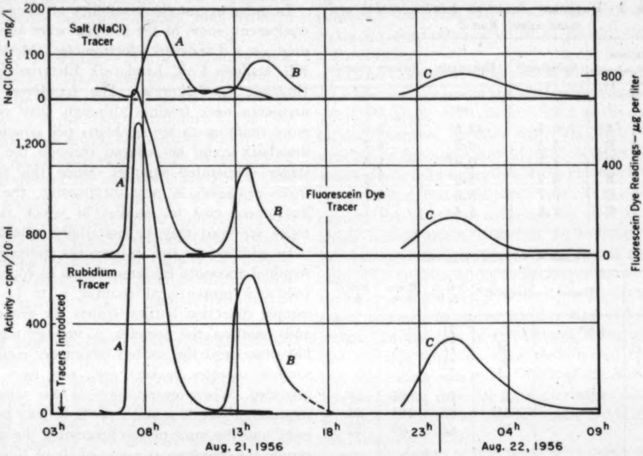

FIG. 2 – **Ottawa River, time of flow using radioactive rubidium, fluorescein dye, and sodium chloride salt tracers; second run, August 21–22, 1956**

it will be noted that the maximum variation amounted to four per cent. The maximum deviations between modal and mean values without regard to location across the stream are summarized in Table 3. Note that the maximum deviations occurred in the initial stretch of the stream from point of introduction to Station A, and that in general smaller differences were noted in the case of the rubidium tracer than the other tracers.

Along with the tracers used herein, on two occasions floats (oranges) were placed in the stream to determine the time of flow between stations. Several dozen oranges were dumped in all, but none were recovered at any of the sampling stations excepting the 0.1-mile section described where floats were constantly attended. They were found lodged in debris along the banks of the stream not far from their point of release.

In Table 4, the actual recovery of each tracer at the downstream stations (B and C) is indicated as a percentage of the amount of tracer passing Station A. Recovery of rubidium was appreciably higher than that for the other tracers. The average rubidium recovery between Stations A and B was 74 pct in the first run, and 65 pct in the second, with no additional loss between Stations B and C. In Run 2, dye recovery at Station B averaged 65 pct of the value at Station A. Thirty-five per cent of the dye was lost between Stations B and C, making the overall recovery 42 pct. Slightly less than 60 pct of the salt passing Station A was recovered at Station B with no further loss of salt in moving to Station C.

Equipment needs for radioactive tracers—Several types of instrumentation may be used in counting radioactive samples, depending in part on the tracer radioisotope used. In this study, as was in-

TABLE 2 – *Deviations obtained based on midstream modal values*

Stations		Rubidium		Fluorescein		NaCl	
From	To	Flow time	Deviation	Flow time	Deviation	Flow time	Deviation
		hr	pct	hr	pct	hr	pct
A	B	6.0 (5.83)	+3.99 +3.19	5.7 (5.7)	−1.22 +0.89	5.6 (5.53)	−2.95 +3.90
A	C	17.25 (17.28)	+0.58 +1.83	17.5 (16.9)	+2.04 −0.41	16.7 (16.72)	+2.62 −1.47
B	C	11.25 (11.45)	−1.14 +1.24	11.8 (11.2)	+3.69 −0.97	11.1 (11.28)	+2.46 −0.27

Mean values in parentheses.

TALBE 3 – *Maximum deviations between modal and mean values, Run 2*

Stations		Rubidium^{86}	Fluorescein	Sodium chloride
From	To			
		pct	pct	pct
O	A	9.8	14.6	6.6
O	B	3.3	6.5	4.7
O	C	1.7	0.47	1.3
A	B	2.9	5.6	8.1
A	C	0.7	3.6	0.1
B	C	1.8	5.4	1.7

TABLE 4 – *Tracer recovered*

Run	Tracer	Location[a]	Reach A–B	Reach B–C	Reach A–C
1	Rb^{86}	L	71	...	...
		M	77	...	...
		R	73	...	...
2	Rb^{86}	L	70	95	66
		M	62	104	65
		R	63	99	62
	Dye	L	61	...	...
		M	66	65	42
		R	59	...	...
	Chloride	L	59	...	...
		M	56	117	66
		R	58	...	...

[a] L, left bank; M, midstream; R, right bank.

dicated earlier, field instruments were tried, and it was found that the Berkeley Field Scaler could be used with a rubber-encased probe. A survey meter attached to a rubber-encased probe did not give sufficient sensitivity. Satisfactory laboratory-type instruments include any of the available conventional instruments such as the G-M end-window counter, the internal gas proportional counter, or where a gamma-emitting isotope is used, a scintillation counter. The latter type of instrumentation has the additional advantage that processing of the sample prior to counting is avoided. In the case of the end-window and proportional counters, such processing is prerequisite. Another disadvantage of the use of the internal gas proportional counter, particularly if taken out into the field, is that a source of counter gas is needed, which means additional equipment to be transported. The internal proportional counter, however, because of its high counting efficiency, gives high sensitivity without inordinately long counting times. In addition it enables the activity to be followed over larger dilutions.

In order to test the possibility of using simpler equipment, some of the samples were also measured on a Landsverk electrometer (Model L-75 KB Analysis Unit, Landsverk Electrometer Co., Glendale 4, California). The Landsverk measurements were feasible although they required more time; up to several hours per sample. This drawback could be reduced through the use of larger evaporated samples. Since this type of instrumentation is very inexpensive, the initial instrument cost for studies in which radioisotopes are used may be materially reduced.

In addition to the instruments indicated, the required accessory equipment such as counter gas (where a proportional counter is to be used), sample collection bottles, dishes for evaporating and counting the samples, a voltage regulator, hot plate, and the normal laboratory equipment such as pipettes, beakers, etc., will have to be provided. Where evaporation of the samples is required, about 30 samples per hour may be processed and the same person processing the samples can do the counting, at a rate of about 10 samples per hour on a single instrument.

Equipment needed for fluorescein determinations—For this purpose a Model B, Beckman spectrophotometer was used. It is quite obvious that this type of instrumentation like the G-M end-window counter, the internal gas proportional counter, or the scintillation counter, cannot be used directly in the field, but may be set up in a temporary laboratory with suitable line voltage. It may be possible to get some concept of fluorescein concentrations through the use of calibrated Nessler-type tubes. Sensitivity may be low, but it may be possible to get some idea of when the peak concentration passes the sampling point and when sampling can be stopped.

Samples may be run without any processing, except sedimentation. About 10 to 15 samples may be run per man hour. Ordinary laboratory glassware may be used. Dye tracing has certain obvious advantages in that rough estimates with visual observations only are possible. Time of passage, current characteristics, and sampling for other tracers can be controlled more readily in its presence.

Equipment for chloride determinations—No special equipment is necessary in running chlorides. If desired, analyses may be made in the field, but it is more convenient to carry them out in the laboratory. About 10 to 12 samples may be titrated per man hour if single analyses are made per sample. This number will be cut in half if duplicate samples are analyzed. The equipment needed includes burettes, beakers, and standard solutions.

Costs and limitations—Where instrumentation is available for making the determinations indicated, the principal costs will be for the procurement of the specific tracers used, and in the man hours required to collect the samples and to process them. As indicated above, the amount of time needed to process the samples is about the same in each instance. Processing will be required in the case of samples counted for radioactivity and for chloride determinations; none being required for processing the fluorescein samples. No processing would be required for a gamma-emitting radioisotope counted with a gamma scintillation counter.

In our case, the cost of procuring the needed tracers amounted to approximately $60 for 300 mc of rubidium^{86}, $50 for six pounds of fluorescein, and $40 for 3000 pounds of sodium chloride exclusive of handling. If the basic instrumentation needed for making such a study is not available about $1000 will be needed to purchase an internal gas flow proportional counter and about $200 to $300 for other accessories. A Beckman Model B spectrophotometer would cost approximately $500 if one is not available. No other equipment will be needed to determine fluorescein concentrations. In the case of chloride determinations, no specialized equipment is needed. If one wished to monitor or make chloride determinations directly in the field, it would be possible to do so using a conductivity cell, but there are certain limitations on the use of this equipment. It could not be used in this case because of the presence of an oily film on the surface of the stream.

One limitation on the use of radioactive materials as tracers is that they be compatible with the water under test. One would not want to use a radioisotope that is quickly precipitated, adsorbed, or metabolized. To minimize adsorption or metabolism of the radioisotope an isotopic or chemically related carrier is added. Since the radioisotope itself is used in such small concentrations on a weight basis, there is no danger of materially affecting the specific gravity of the solution under study as may happen with sodium chloride or other added salts. Furthermore, color which interferes with the use of dye tracer does not affect the use of a radioisotope. Turbidity influences the use of fluorescein and radioisotopes, particularly if the radioisotope is readily adsorbed. As stated above, to counteract this adverse effect, one would add carrier to the radioisotope. In the fluorescein samples it was found that the addition of alumina cream for clarification resulted in variable losses of fluorescein.

Sodium chloride or other similar salts would be unsatisfactory for use in streams having a variable chloride content. Also any ions, such as the other halides, cyanides, or other materials, that react with silver ion could not be used because they would give a false indication of the chloride levels in the stream. Since the titration involves a color change, the technique could not be used with a highly colored waste or stream. In addition, the increase in specific gravity that would occur might result in a layering of the added tracer and a false indication of flow time. This would be particularly true if one were measuring the flow time of a deep stream. In the case of the Ottawa River which had variable stretches, some shallow and ripply and other deep ponds, the effect of the variable specific gravity may not have exerted as marked an influence as it would in the case of a slow moving rather deep stream.

Mixing of NaCl in the stream is a critical factor in the use of this as a tracer. During this study, a saturated brine solution was added to the flow in the refinery outfall channel. A high velocity, a Parshall flume, a two-foot cascade, and about 50 ft of riffled area should have accomplished good mixing. However, mixing was not complete, as the chloride concentrations in a pool of about 2½ ft depth immediately below the riffled area showed concentrations more than twice as high at the 25-inch depth as at the 2-inch depth even after more than seven hours after introduction. As shown in the results, this factor contributed to a somewhat longer passage time to and poor recovery at the first sampling station. Good recovery and consistent behavior were evident at subsequent stations.

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Radiotracer Experiments in the Mohawk River, New York, to Study Sewage Path and Dilution

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Abstract—Sewage from the Knolls Atomic Power Laboratory near Schenectady, N. Y., was dosed with 4.53 curies of P^{32} prior to discharge into the Mohawk River. Its pattern of diffusion was measured in the river with immersible GM-tubes and by sampling. The initial path of sewage was strongly influenced by differences in density between sewage and river due to temperature. During warm months relatively cold sewage moved on the river bottom perpendicularly to river current. For at least the first 800 ft of travel the maximum sewage concentration decreased logarithmically with distance from outfall. The term 'half-distance' (here about 110 ft) is proposed to describe the concentration change. During cold months sewage rose to the river surface and at times was moved upstream by wind. However, when the river temperature was near freezing, the sewage first rose and then sank as the temperature of the sewage-river mixture approached 39° F.

Introduction—Studies sponsored by the Atomic Energy Commission and conducted by the U. S. Geological Survey on the Mohawk River, at and downstream from the Knolls Atomic Power Laboratory (KAPL) near Schenectady, N. Y., provide data on river hydrology, quality of water, suspended sediment, and river-bottom materials. As part of these studies, three radiotracer experiments were performed in 1953–54 to determine the path and dilution of KAPL sewage under various river conditions. This paper, which is based on a report [*Simpson*, *Beetem*, and *Ruggles*, in preparation], describes the third and most extensive experiment, but draws on the data of the two preceding ones in presenting interpretive conclusions. The exploratory nature of the work made it necessary to begin in a small way and build each experiment on the results of the preceding ones.

Additional data were obtained through the participation of two independent groups: (1) a New York State Department of Health group collected and analyzed river-water samples from a series of stations between KAPL and Cohoes, some 14 miles downstream; (2) a Harvard University group collected samples and made measurements with an immersible GM-tube in various places near the KAPL sewer outfall. The *New York Department of Health* [1954ab] data was subjected to an interpretive study by *Parker* [1955] of the Harvard Group, but the Harvard data have not been published.

Location and hydrologic and physical conditions—KAPL is in east-central New York near the city of Schenectady, on the right (south) bank of the Mohawk River, about 15 miles upstream from its confluence with the Hudson River at Cohoes (Fig. 1). From Cohoes to KAPL and for many miles upstream, the Mohawk River is part of the Erie Canal system. As such it consists of a series of navigation pools, each impounded behind a permanent or a movable dam. In this study we are concerned mainly with two pools, one at KAPL impounded behind a dam at Vischer Ferry, herein called Vischer Ferry pool, and the pool immediately below it, herein called Crescent pool. Vischer Ferry pool extends from Vischer Ferry dam, which is about 1.7 miles downstream from KAPL, to a movable navigation dam at lock 8, which is about 9.0 mi upstream from KAPL, giving a total pool length of 10.7 mi. The average width of this pool is 940 ft. The minimum channel depth maintained for navigation is 14 ft, but near KAPL a maximum pool depth of 36 ft occurs; average depth at the KAPL section is about 20 ft, and width is about 700 ft. The quantity of water impounded between KAPL and Vischer Ferry dam when the pool is at flashboard crest is about 130,000,000 ft^3, about 10,000,000 ft^3 being impounded per foot of depth for the top three feet. Total pool impoundment is approximately five times greater than that contained in the section between the dam and KAPL.

Vischer Ferry dam is a permanent concrete dam serving both navigation and the production of hydrolectric power. It is 1920 ft long and 36 ft high, with a crest elevation of 211 ft above sea level. Flashboards 2¼ feet high are installed during about ten months of the year. The hydroelectric power station at the left (north) end has a capacity of about 3000 cfs, but operation is intermittent during summer and fall because river

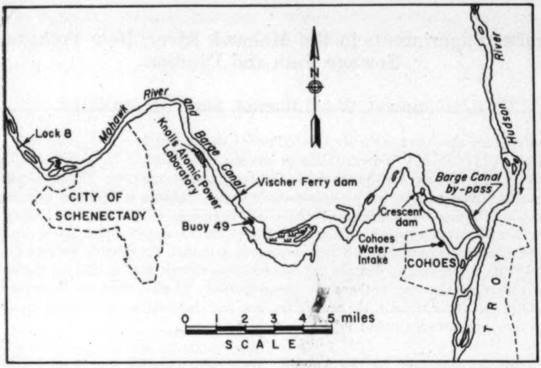

FIG. 1 – Lower reach of Mohawk River showing location of KAPL

discharge is less than station capacity. Lock 7 of the barge canal is at the right (south) end of the dam. Discharge resulting from lockage and leakage averages about 100 cfs. Spillage over the dam ordinarily occurs only during annual spring floods and takes place along the full length of the dam; at other times minor spillage can usually be discharged through waste gates near the hydroelectric power station. River sediment to a maximum thickness of 20 ft has accumulated in the pool on the upstream side of the dam.

Crescent pool extends from Vischer Ferry dam downstream about 9.6 mi to Crescent dam. This dam also is of concrete and also is operated in conjunction with a hydroelectric power station; operation of the two dams is roughly similar.

The discharge of the Mohawk River (drainage area 3456 sq mi) is gaged at Cohoes, about 14 miles downstream from KAPL. There is no important tributary between Cohoes and KAPL, and average daily discharge at the two places is virtually identical. Average discharge since 1918 is about 5700 cfs. Low-flow discharge during the summer and early fall is about 1000 cfs; during August 1954, when Test 3 was performed, discharge out of Vischer Ferry pool was roughly as follows: 2000 cfs between 6h 00m and 18h 00m, and about 100 cfs for the remaining 12 hours of each day.

Isotope discharge—Test 3, begun August 9, 1954, was designed to obtain hydrological data at a time when KAPL sewage was cooler and denser than river water. Sewage temperature was 68°F and river temperature was 76°F. On the basis of temperature alone, the sewage was about 0.10 pct denser than river water.

Beginning at 09h 08m (EST) and ending at 12h 20m, 31.60 liters of an aqueous solution of KH_2PO_4, containing 4.53 curies of phosphorus^{32}, was discharged at a constant rate into the Mohawk River through the KAPL sewer, or at an average discharge of 23.6 millicuries per minute (mc/min). The rate of sewage discharge was 200 gal/min (gpm), or 756 liters per minute. Hence, the average concentration of isotope leaving the sewer outfall was 31.2×10^{-6} millicuries per milliliter (mc/ml).

P^{32} was chosen as the radioisotope because (1) it is relatively harmless; (2) it emits short-range beta particles only, making it relatively simple to measure concentration with immersible GM tubes; (3) it has a convenient half-life of 14.3 days.

The isotope-sewage mixture flowed through 56 ft of 30-inch concrete pipe between the manhole where the isotope was introduced and the outfall on the river bottom. The outfall is about 15 ft offshore and under a depth of water that varies with river stage but averages about eight feet. About two-thirds of the 56-ft length is submerged below river level. Measurements made in Test 1 when sewage was warmer than river water showed that the isotope and sewage were not completely mixed at the outfall, and that the maximum isotope concentration of the sewage was twice the average. Although a similar measurement was not made in Test 3, it will be assumed that the same relationship prevailed, and that the maximum isotope concentration at the outfall was twice the average, or about 60×10^{-6} mc/ml. This is equivalent to about 140×10^{3} disintegrations per minute per milliliter (dpm/ml).

Measurement of isotope in river and interpretation of data—The path and concentration of the sewage-isotope mixture was measured in the river in two ways: (1) immersed GM-tubes with appropriate scalers powered by portable A C generators gave on-the-spot measurements at the river sections shown on Figure 2 and elsewhere as mentioned, and (2) collections of river-water samples for subsequent laboratory analyses. The data obtained with immersible GM-tubes will be considered first.

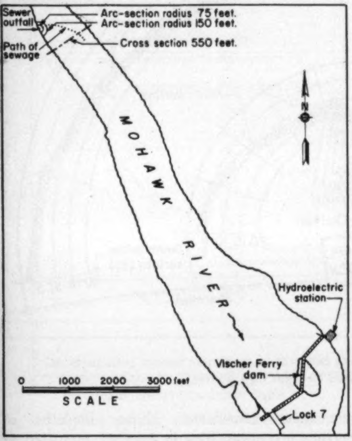

FIG. 2 – Mohawk River between KAPL and Vischer Ferry Dam showing location of sewer outfall, location of sections measured with immersible GM-tubes, and path of sewage, Test 3

Data from immersible GM-tubes—GM-tube measurements were made from three different boats: a catamaran as shown on Figure 3, a buoy tender borrowed for the occasion from the New York State Department of Public Works, and a rowboat. The catamaran and buoy tender carried all instruments aboard, but the rowboat carried only a GM-tube on a 200-ft lead, the remaining instruments being set up on the KAPL dock. The rowboat was attached to the dock by a rope line. During the three-hour period of isotope discharge, the rowboat measured concentration in two circular arc sections, one of a radius of 75 ft from the dock and the other of a radius of 150 ft. The sewer outfall was about 10 ft from the center of curvature.

Figure 4 shows isopleths of maximum isotope concentration in dpm/ml, plotted on polar coordinates, based on the maximum concentration measured at each point occupied by the GM tube. The GM-tube readings, in counts per minute (cpm), were converted to dpm/ml by the relation dpm/ml = 2 × cpm as obtained empirically for the tubes by laboratory test. As shown by the isopleths, sewage moved in a relatively narrow path down the slope of the river bottom, nearly

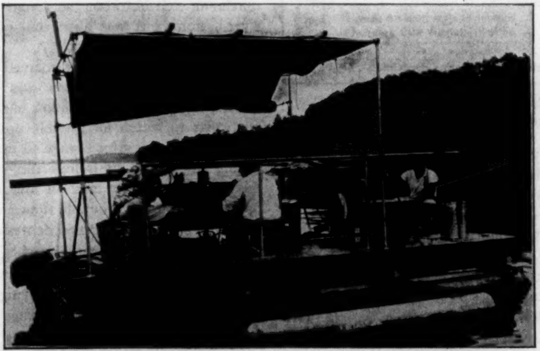

FIG. 3 Catamaran with radiological instruments on Mohawk River during Test 3; an immersed GM-tube is suspended from plank on each end of boat, and boat is tied to tagline stretched across river

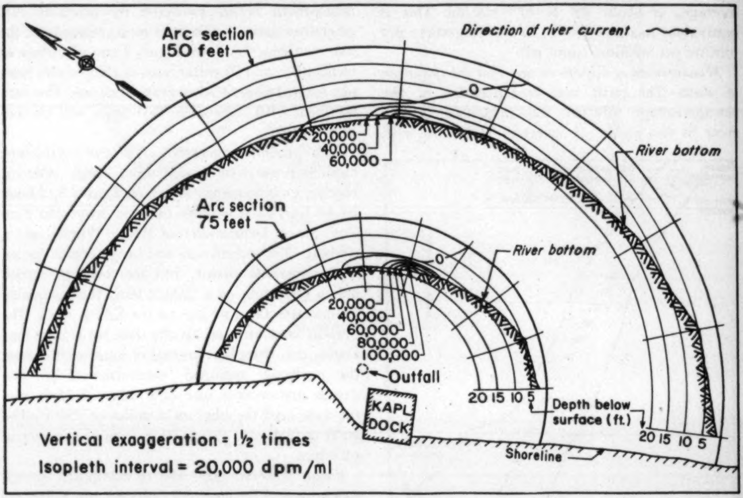
Arc section
150 feet
Direction of river current
0
20,000
40,000
60,000
River bottom
Arc section
75 feet
0
River bottom
20,000
40,000
60,000
80,000
100,000
Outfall
KAPL DOCK
20 15 10 5
Depth below surface (ft.)
20 15 10 5
Shoreline
Vertical exaggeration = 1½ times
Isopleth interval = 20,000 dpm/ml

FIG. 4 – Plan and section views of arc sections showing isopleths of maximum isotope concentration, Test 3; section views are plotted on polar coordinates

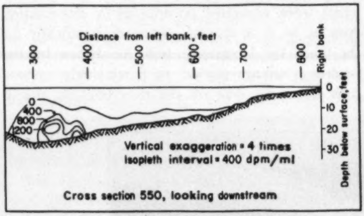

FIG. 5 – Cross section 550 showing isopleths of maximum isotope concentration, Test 3

perpendicularly to the direction of river flow, for at least 150 ft. River discharge at the time was about 2000 cfs and average river velocity in this zone was on the order of 0.1 ft/sec. The change in concentration with distance from the outfall will be discussed later.

While the rowboat was making its measurements, the catamaran surveyed a river cross section 550 ft downstream from the outfall. The catamaran was attached to a tagline stretched across the river, and the tagline served both as anchor and as position marker. Figure 5, plotted on rectangular coordinates, shows isopleths of maximum concentration in dpm/ml, measured at this section. The main concentration of sewage here was flowing close to the deepest part of the river channel and its direction presumably was about parallel to that of river flow; however, the maximum concentration no longer was on the river bottom, but was about one-quarter of the way up.

Finally, the buoy tender roamed between the rowboat and the catamaran and in upstream waters, to try to define the path of sewage and in particular to watch for possible upstream movement. No tendency for sewage to move upstream during the period of isotope discharge was detected. (The deepest part of the river bottom opposite the KAPL outfall slopes upstream toward the bottom of a closed depression. It seems possible that during periods when the hydroelectric plant is shut down and river discharge is near zero, relatively dense sewage might move into the depression.) The path of sewage based on all GM-tube measurements made during the period of isotope discharge is shown on Figure 2.

Each of the three sections surveyed shows a small region where measured concentration of activity was a maximum. It is assumed that steady-state conditions prevailed at the time the maximum measurements were taken. In Figure 6, the log of the maximum measured concentration at each section is plotted against distance from outfall. The three points fall on a straight line. The log of the calculated maximum concentration at the outfall mouth also falls on the same straight line. This relationship indicates that in about the first 800 ft of sewage travel, the distance rate of change of maximum concentration of isotope, and presumably of sewage, at any section was directly proportional to the maximum concentration at that section. By analogy with radioactive decay, it is convenient to speak of a concentration 'half-distance' or the distance of travel over which maximum concentration is reduced by a factor of two. In the case of the present experiment the half-distance was about 110 ft. (Results of Test 2 indicate that when relatively warm sewage rises to the river surface, the half-distance, if it exists at all, is very short. In that test the density difference was quickly dissipated and for at least 500 ft of travel the maximum concentration of sewage apparently was inversely proportional to distance from outfall.)

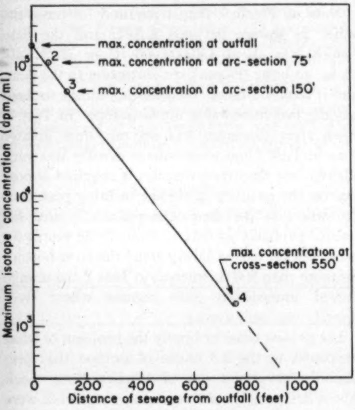

FIG. 6 – Relationship of isotope concentration to distance from outfall

By a simple calculation it becomes obvious that the half-distance relationship is not indefinitely valid. Extrapolating to 1600 ft on Figure 6, it is found that the calculated maximum concentration there would be less than that measured at Vischer Ferry dam, some 7400 ft farther downstream. Hence, it is concluded that, a short distance beyond the 800-ft point, the half-distance relationship is replaced by something else.

Water-sample data—Several hundred samples of

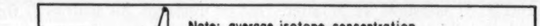

FIG. 7 – Relationship of isotope concentration to time and cumulated river discharge at Vischer Ferry Dam and at Buoy 49, Test 3; Vischer Ferry Dam is about 1.7 mi and Buoy 49 is about 2.8 mi below outfall

river water were taken and analyzed by the three participating groups. These data and their interpretation appear in the publications listed under REFERENCES. In order to round out this discussion of the movement of sewage in Vischer Ferry pool, we shall present part of the data obtained at Vischer Ferry dam. Figure 7 shows the concentration of isotope, corrected for radioactive decay, passing through the forebay of the power station, plotted against cumulative river discharge from the time isotope discharge began at KAPL. The isotope concentration (in millicuries per 1000 cfs hr, which equals millicuries per 3,600,000 ft^3) was calculated from hourly samples taken by the Department of Health. The area under the curve measures the quantity of isotope that flowed past the dam. Under the main hump this quantity is 3.0 curies or 66 pct of the total original dose. If the two small humps in the tail of the curve also be included, the quantity is 3.2 curies or 71 pct of the dose. For the sake of comparison the data collected at Buoy 49, about a mile below the dam, are similarly plotted on the same figure. The percentage of total dose passing this station was about 60 pct.

Maximum concentration at Vischer Ferry dam was 2.96 dpm/ml (equals 136 mc/1000 cfs hr as shown on Fig. 7), measured 36 hr after isotope discharge began. The calculated maximum at the sewer outfall was 140 × 10^3 dpm/ml, and the maximum concentration at section 550 was 1.5 × 10^3 dpm/ml (Fig. 5) measured 4½ hr after isotope discharge began. Extrapolating on Figure 6 to a distance of 800 ft from the sewer outfall we estimate that in this interval the isotope was diluted 140 fold. In the remainder of the distance to the dam, some 8200 feet, the isotope was diluted an additional 330 fold. Or, nearly one third of the dilution occurred in about one tenth the distance between outfall and dam. Actually, the relative dilution close to the outfall must be greater than these figures indicate. Close to the outfall the three-hour-long discharge of isotope can be considered as a continuous point source insofar as the immersible GM-tube measurements are concerned, but at the dam the three-hour discharge is more nearly an instantaneous point source insofar as the hourly samples are concerned. If we were to compute the dilution at the dam considering KAPL sewage as a continuous point source, then the maximum dilution available is simply the ratio of river discharge to sewage discharge, which was about 2000-fold at the time of the test. Hence, if the dilution of maximum concentration in a continuous point source was about 140 fold in 800 ft, then the remaining 8200 ft could provide only another 14 fold dilution. It appears probable that the initial density difference between river water and sewage resulted in faster dilution in terms of distance from outfall than would have occurred in the absence of a density difference.

Note on Figure 7 that it required 1.3 times the water in storage between KAPL and the dam (which was about 130,000,000 ft^3 or 36 × 10^3 cfs hr) to bring the peak concentration to the dam, and it took 4.3 times the water in storage to flush out the last measurable bit of isotope. In Test 2, when river discharge was several times greater than in Test 3 and when sewage density was very slightly less than river density, it required almost exactly the quantity in storage to bring peak concentration to the dam. The reason for the difference probably is that in Test 3 the relatively dense sewage moved slowly along the river bottom for more than 800 ft, whereas in Test 2 the sewage moved immediately into regions where river velocity was near average.

Let us now consider briefly the problem of what happened to the 1.3 curies of isotope that presumably never got out of Vischer Ferry pool. About 250 samples of river-bottom materials were taken from 46 different locations in the pool in the three-week period following the day of isotope discharge. About 50 samples were taken prior to isotope discharge. An analysis of the results discloses that not more than 0.2 curie can be accounted for by adsorption of isotope on the river bottom. Therefore, the remaining 1.1 curie either was taken up by aquatic life that did not float out of the pool, or it did leave the pool but was unmeasured because of faulty sampling procedure. However, (1) the next two downstream sampling stations showed a regular decrease in quantity of isotope passing (concentrations at stations still farther downstream were too low to permit this calculation), and (2) results of analyses made at KAPL and at the Department of Health, for places where sampling overlapped, were nearly the same, thus tending to rule out systematic laboratory errors; therefore, we conclude that aquatic life probably was responsible and that such things as eels and fish and water chestnut took up about a curie of P^{32} in a period of 2½ days.

In closing we wish to mention a series of measurements made with an underwater resistance thermometer in December 1953. These measurements serve to illustrate the importance of density differences in controlling the path of sewage. It was found that when river temperature was near freezing, sewage first rose to the river surface; then, as sewage mixed with river water and approached a temperature of 39°F, the mixture sank to the river bottom. The rising and sinking occurred within the first 50 ft of sewage travel.

Acknowledgments—The experiments described in this paper are part of a larger program sponsored by the U. S. Atomic Energy Commission. The cooperation and assistance provided by the Health Physics unit of KAPL, under L. J. Cherubin, Supervisor are gratefully acknowledged. The Health Physics unit prepared and discharged the isotope, supplied the necessary radiological instruments, performed hundreds of radioanalyses of samples of water and mud, and provided technical counsel in almost all aspects of the work.

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Radioactive Tracers in Hydrologic Studies

FRANK L. PARKER

Abstract—The use of radioactive tracers to study phenomena in hydrology that have not previously been easily amenable to investigation is proceeding at a rapid pace. A group of experiments was carried out in lakes and reservoirs in Massachusetts to determine eddy diffusion coefficients. The average eddy diffusion coefficient divided by the radius of the eddy was found to be 0.09 ft/sec. A group of experiments to determine the average velocity of streams and the dilution in streams by use of radioactive tracers was then performed. The diffusion coefficients found in the test of the streams were compared with the theoretical diffusion coefficients of G. I. Taylor for straight pipes and found to be larger due to the increased dispersion caused by bends and obstructions in the stream. A mathematical formulation for general use in determining dilution and dispersion in rivers and streams by radioactive tracers was established. A correction is made for the absorption and decay of the isotope depending upon its chemical and nuclear properties. Work is under way at Harvard University to delineate further the absorption coefficients of important isotopes under various conditions leading to a better determination of the eddy diffusion coefficient.

Radioactive tracers are becoming an important tool for hydrologic studies because of the low cost, ease of detection, small gravimetric quantities required, and absence of density problems. The tracer to be of maximum usefulness must (1) have a half-life long enough to remain detectable for the length of the experiment, (2) have beta or gamma energies, or both, sufficiently energetic so as to be easily detectable by Geiger-Müller tubes or scintillation crystals, and (3) must function as an integral portion of the water and not be absorbed, adsorbed, or exchanged preferentially.

No one tracer will fulfill all these qualifications for all tests but for most tests it is possible to choose some tracer that will satisfactorily fulfill the above requirements. Isotopes of various half-lives and energies are available and so the one best fitting the conditions of the test can be chosen. Anions, amphoteric ions, and complexed ions are usually least sorbed or exchanged and so should be chosen if possible. For many tests iodine^{131} with a half-life of 8.05 days, or ruthenium^{106} with a half-life of one year, will be satisfactory. For other tests complexed scandium^{46}, half-life 85 days, or cobalt^{60}, half-life 5.26 years could be used. Shorter half-lives are preferable so that the tests may be repeated without any activity from earlier tests influencing the results. Only one per cent of the initial activity still remains after 6.5 half-lives and after ten half-lives 0.1 pct of the original activity is present.

There are, of course, certain disadvantages to the use of radioactive tracers. (1) They are hazardous and suitable precautions must be taken. (2) Expensive electronic equipment is necessary for detection. (3) A rigid time table must be followed particularly if isotopes with a short half-life are used.

However, the sensitivity of detection and the lack of density effects would seem to outweigh these disadvantages. Fluorescein, the most commonly used tracer in hydrology, can be detected in concentrations as low as 10^{-1} parts per billion. Radioactive iodine^{131}, in contrast, can be detected by scintillation counting in concentrations as low as 10^{-7} parts per billion.

Previous uses of radioactive tracers—The first inadvertent use or misuse of radioactive materials in hydrology came after the explosion of the first atomic bomb at Alamogordo, New Mexico, in July 1945. The amount of radioactive fallout from this explosion was sufficient to contaminate the Wabash and Iowa Rivers at distances from the bomb of more than 1000 miles and to cause the fogging of photographic film packed with strawboard processed with water from these two rivers [*Webb*, 1949, p. 375].

In August 1946 the explosion of the underwater bomb at Bikini enabled *Munk* and coworkers [1949] to measure eddy diffusion coefficients by the spread of activity in Bikini Lagoon.

Since then, the detention time in ponds has been measured with iodine^{131} [*Archibald*, 1950, p. 111], scandium^{46} has been used to determine the movement of sand grains in the bedload of the Thames River [*Putnam* and *Smith*, 1956], and radioactive silver has measured the movement of sand grains along the sea floor [*Gilbert* and others, 1955].

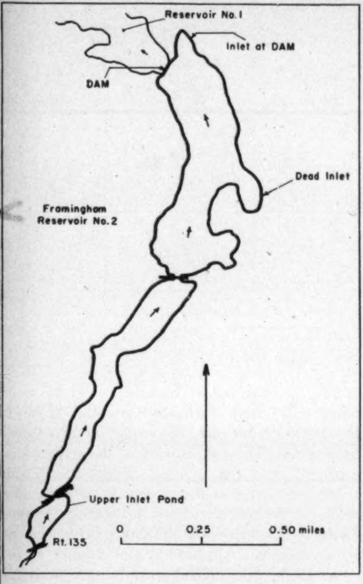

FIG. 1 – Map of the Framingham reservoirs of the Boston water supply system

Eddy diffusion coefficients have been measured by iodine^{131}, phosphorus^{32}, and rubidium^{86} [*Parker*, 1955] and dam sites have been investigated for possible piping by iodine^{131}, bromine^{82}, and chromium^{51} [*Hours*, 1955]. Sources of supply of water for wells have been determined by bromine^{82} and rubidium^{86} [*Hours*, 1955; *Fox*, 1952], and the rate of underground movement of waters measured by ruthenium^{106}, strontium^{89}, and cesium^{137} [*Kaufman* and *Orlob*, 1956; *Parker* and *Cowser*, 1957].

Eddy diffusion coefficients determined through use of radiotracers—Since 1951 a series of tests have been run at Harvard University to evaluate the dilution of radiocontaminants in surface waterways. To determine the dilution, it is necessary to measure the diffusion of the material. Since molecular diffusion is so much less than eddy diffusion the studies were restricted to eddy diffusion.

By eddy diffusion is meant the mass transfer of molecules in eddies of various sizes throughout the entire volume. The equation for the eddy diffusion coefficient is the standard Fick's equation.

$$\partial c/\partial t = \alpha^2 \partial^2 c/\partial x^2 \tag{1}$$

where c is the concentration
x is the distance from the dosing point
α^2 is the eddy diffusion coefficient.

For the two dimensional case (1) becomes

$$\partial c/\partial t = \alpha^2 \partial^2 c/\partial r^2 + (\alpha^2/r)\partial c/\partial r \tag{2}$$

where r is the radial distance from the dosing point.

The eddy diffusion coefficient was measured in a number of tests in the old Framingham Reservoirs of the Boston water supply system. These are out-of-service reservoirs on a standby basis and so the water is not used for drinking, bathing, or boating. The general area is shown in Figure 1.

The tests were performed by the instantaneous release of the activity into the reservoir from a bottle carried at fish pole length from a row boat. The dose varied from 2 to 20 millicuries of iodine^{131}. The water was then sampled as shown on Figure 2. By a solution of (2) the concentration is equal to

$$c = (M/4\pi\alpha^2 t)e^{-r^2/4\alpha^2 t} \tag{3}$$

where M is the amount of radioactive material initially added per foot of depth. Solving for the eddy diffusion coefficient, the average value of the eddy coefficient divided by the radius of the eddy was found to be 0.09 feet/second. This is the form of presenting eddy diffusion coefficients recommended by *Munk* and others [1949]. The execution of the test was much simpler than the previous techniques of dropping dye from planes and photographing their spread or of dropping mimeograph paper from airplanes and measuring its spread from photographs taken at intervals.

A series of tests was also run in an out-of-use pipeline connecting two of the Framingham reservoirs. A plot of one of the test results is shown in Figure 3. Analyses of the tests were made by a solution of the equation of pipeflow.

$$c = (w/2r^2\pi^{3/2}\sqrt{\alpha^2 t})e^{-(x-\mu t)^2/4\alpha^2 t} \tag{4}$$

where r is the radius of pipe
w is the mass of activity
μ is the mean velocity

The average eddy diffusion coefficient for the pipeline tests was 4 ft^2/sec. This value was determined by use of Thomas' [*Parker*, 1955, p. 4–20] non-parametric solution and Taylor's solution [*Taylor*, 1954, p. 446].

A final experiment was the determination of

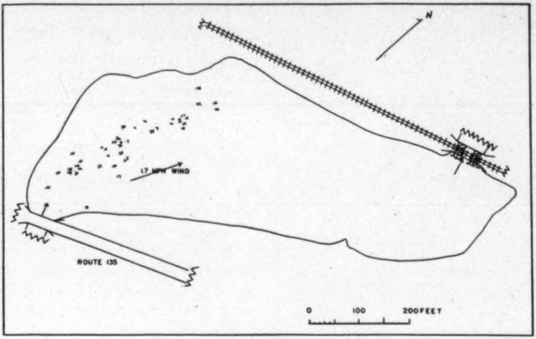

FIG. 2 – Sampling sites of reservoir test

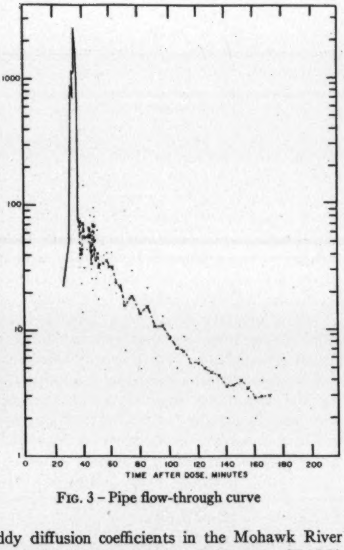

FIG. 3 – Pipe flow-through curve

eddy diffusion coefficients in the Mohawk River at the Knolls Atomic Power Laboratory (KAPL) (Fig. 4). The sampling stations of interest are KAPL, Vischer Ferry Dam, Buoy 49, Buoy 18B, and the Cohoes water plant. The first of three tests was primarily to check the instruments. During the second test, heavy concentrations of fallout material masked the tracer and this will continue to be a problem as long as bomb testing continues.

During the third test in August 1954, 4.5 curies of phosphorus^{32} were discharged into the Mohawk River through the plant sewer pipeline in a three-hour period. The temperature of the river water was 76°F and that of the effluent 68°F. The average discharge of the river was 1100 cfs. The results of the test are shown in Figure 5. As predicted by theory, as the activity proceeds downstream there is a reduction in peak heights, an increase in the longitudinal spread of the activity, and a reduction in the total amount of activity passing the sampling station. The reduction in activity due to flocculation and sedimentation, absorption, and biological uptake is here called the river absorption coefficient, N. It is postulated that this reduction may be fitted by an exponential decay law. Then by use of (4) and taking into account the nuclear decay and river absorption, we have

$$c = (w/2r^2\pi^{3/2}\sqrt{\alpha^2 t})e^{-(x-\mu t)^2/4\alpha^2 t}e^{-(N-\lambda)t} \qquad (5)$$

where λ is the nuclear decay coefficient

N is the river uptake coefficient.

Since (4) affects only the distribution of the activity flux curve and not the area under the curve the total amount of activity passing the downstream station corrected for nuclear decay and river absorption must equal the amount dosed.

By plotting the detention time for the perfect tracer, no decay or river absorption, against the proportion of the initial dose flowing past each station (Fig. 6), it was possible to get an average decay and river absorption coefficient, 0.0156 per hour. Since the nuclear decay coefficient is known for phosphorus^{32}, 0.0021 per hour, the

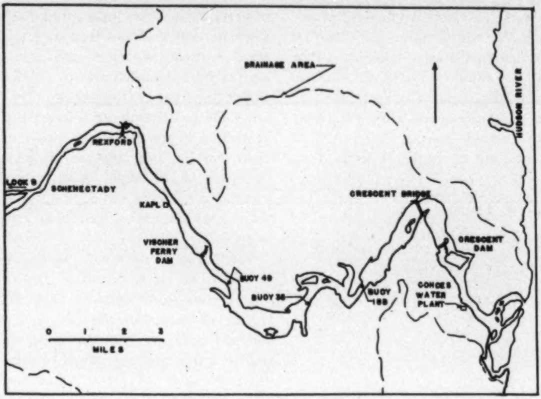

FIG. 4 – Map of the Mohawk River test area

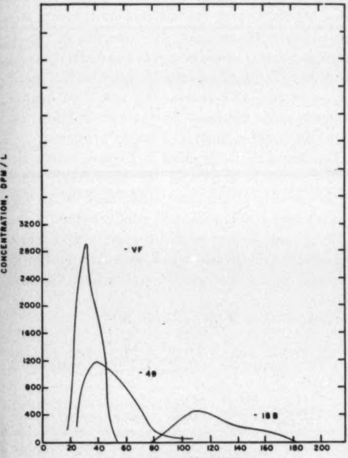

FIG. 5 – Mohawk River flow-through curves

coefficient for river absorption is calculated to be 0.0135 per hour.

The results of the test are shown in Table 1. The activity in samples from the Crescent Dam power house, located at the dam, and the Cohoes water plant were too close to background to be distinguished from background. Note that the eddy diffusion coefficients for the test are a good deal larger than the theoretical values. This is to be expected since the theoretical equation is based upon uniform and straight pipelines and the river is far from this. From an extension of the data from the flow-through curves the time to Cohoes water plant was computed to be 217 hours and the activity passing was 3.3 pct of the original dose. From an extension of the data of the eddy diffusion coefficients determined for the other reaches in the river, it was computed that the eddy diffusion coefficient for the river to mile 13, Cohoes water plant, was equal to 100 ft squared per second. If the conditions that prevailed during the test held throughout the year it was calculated that under steady state conditions 1600 curies of phosphorus^{32} could be injected into the river at KAPL each day and still have the concentration at the Cohoes water plant less than ten per cent of the maximum permissible concentration for phosphorus^{32} (2×10^{-5} microcuries per milliliter). By use of the maximum permissible concentrations for other isotopes and with other river absorption coefficients and nuclear decay coefficients, it would be possible to compute the maximum amount of other isotopes that could be discharged to the stream without downstream hazard.

Though it is true that most streams have demands for phosphorus and other radioactive materials, the extent of the demand is dependent upon a wide variety of physical, chemical, and biological conditions. Therefore, an analysis of this type must be used with caution until further experimentation has justified its reliability. It is conceivable that the amount of activity absorbed by the river could be released at a later date because of unusual water conditions. However, under the circumstances prevailing at the Knolls Atomic Power Laboratory and on the basis of the tests run and the analyses made, it has been possible to discharge low-level wastes safely into the Mohawk River without hazard to the downstream users and at substantial savings to the Knolls Atomic Power Laboratory. Downstream checks, of course, are made to determine whether there is any concentration of activity in the mud and biota. Further work is continuing at Harvard University under an AEC contract to evaluate the river absorption coefficients and eddy diffusion coefficients under a wide variety of conditions for a number of isotopes.

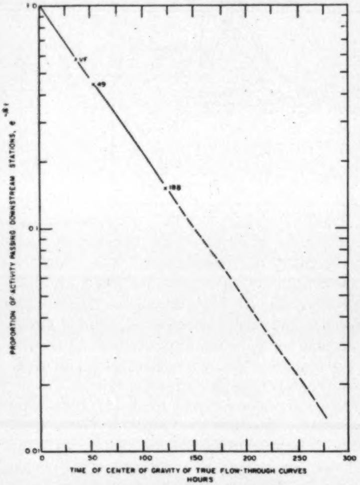

FIG. 6 – Plot of the relationship of detention time to the proportion of the initial dose passing to give combined decay and absorption coefficient

Future uses of isotopes in hydrology—Some other possible uses for tracers might be to investigate the relation of rivers with their tributaries by taking advantage of the fact that most of the radioactive fallout occurs as washout in the rain and so if the tributary should be rained upon and the main stem not, a free tracer would be available; the same test, of course, could be run with a prepared tracer limited only by the cost of the tracer. The investigation of the solitary wave could be facilitated by the use of tracers and particularly the amount of exchange of water between the wave and the rest of the water could be measured. The same measurements could be made for surges and this information would be helpful in determining dilutions downstream obtained by releasing large quantities of water upstream.

The Mohawk River data in Figure 5 were obtained from the report of the New York State Department of Health on the Mohawk River test which was a cooperative test administered by the U. S. Geological Survey with the New York State Department of Health, the Knolls Atomic Power Laboratory, and Harvard University participating.

TABLE 1 – *Per cent activity passing downstream stations Mohawk River, August 1954*

Station	River miles from KAPL outfall	Date and time of observed peak	Per cent passing	Per cent passing corrected		Time to center of gravity of flow-through curves		Eddy diffusion coefficients	
				For nuclear decay	For self purification	Actual tracer	Perfect tracer	Perfect tracer[c]	Perfect tracer[d]
		h m				hr	hr	ft²/sec	ft²/sec
KAPL	0.0	Aug. 9 11 30	100	100	100	0	0	0	0
Vischer Ferry Dam	1.7	Aug. 10 20 00	58.2	62.1	100	34	34	13.5	1.8
Buoy 49	2.8	Aug. 10 24 00	50.4	54.2	100	48.7	50.8	43.4	2.9
Buoy 18B	7.5	Aug. 13 24 00	19.7	24.5	100	118.5	123.3	65.9	3.1
Crescent Dam power house	11.3	[a] ...	[a]	[a]	100	[a]	[a]	...	...
Cohoes water plant	13.0	[a] ...	3.3[b]	[a]	100	[a]	217[b]	...	...

[a] Not sufficient data to be determined.

[b] Extrapolated value.

[c] Method of movements [*Parker*, 1955, p. 4–20].

[d] Theoretical [*Taylor*, 1954, p. 456].

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The Travel Time of Radioactive Wastes in Natural Waters

G. T. BRYANT AND J. C. GEYER

Abstract—Radio isotopes discharged into natural waters (1) precipitate and settle, (2) adsorb on suspended and fixed surfaces, (3) enter the biologic cycle, or (4) in solution move with the flowing, mixing water itself. In the course of its life a single nuclide may shift with more or less freedom back and forth among these alternates. The paper deals with phenomena related to the fourth alternative. Natural waters and the substances carried in solution move and mix in response to complex forces of gravity, wind, tide, density, impact, shear, and inertia. Past studies of mixing and movement are drawn on to depict the time and space distribution of radioactive contaminates in natural waters. Tracer studies offer means for evaluating mixing and travel time which may in turn be used to forecast the fate of wastes continuously disposed of in water.

Water is nature's transportation agent. Through complex combinations of chemical, biological, and physical processes natural waters move everything they touch downward towards the oceans. The rate of attack and transport range from the rapid melting away of coast lines and river banks to the slow dissolution of granite mountains and their gradual transportation through alluvial valleys. Movement of the water itself and in particular the movement of flood waves, have received a great deal of study. In contrast, movement of the materials transported by water has received much less attention relative to its great significance.

Attention, therefore, is directed toward phenomena involved in the transportation of suspended and dissolved substances by the waters flowing down rivers and through tidal estuaries. Such materials may be conservative, that is, not change or disappear, or they may be non-conservative and change form or become inactive in the course of time. Sodium chloride is a conservative contaminant, biochemical oxygen demanding substances are non-conservative.

A radioactive substance is non-conservative only insofar as its activity is concerned. Sooner or later the atoms which produced the activity must find their way downstream. If a steady state were reached, just as many atoms would pass each section of the river as were discharged at the point of contamination. The average time of travel from section to section governs the amount of activity found at each point along a stream. This average travel time is almost always slower than the average rate of movement of the water.

The delay in time of transit relative to the water may be very long for atoms adsorbed on the channel surfaces or incorporated by sedimentation in the bottom sludges. It may be somewhat less but still quite long for atoms which enter the biological cycle. On the other hand, the radio-isotopes that escape detention by sedimentation and adsorption, move along downstream at rates that are at least in the same order of magnitude as the average rate of movement of the water. For this reason the flow time in water courses must be known to predict behavior of the contaminant.

Flow time in rivers by the use of tracers—Several earlier workers, [*Allen*, 1923, p. 285; *Barbagelita*, 1928, p. 789] used chemicals to determine flow times and quantities of flow in hydraulic structures. More recently, *Archibald* [1950], *Thomas* [1954], and *Parker* [1955], have used radio-isotopes as tracers to determine flow times in hydraulic structures and in natural waters. Regardless of the type of tracer used the problem is to predict the behavior of the water or of pollutants introduced to the water in the light of the field data collected from the tracer study.

Taylor [1954] has presented a theoretical analysis for the dispersion of matter in turbulent flow based on the classical diffusion equation with the conditions that the channel be of uniform cross-section, constant net velocity, and constant eddy diffusivity. He arrives at a solution of

$$C = M/2A\ \sqrt{\pi K t}\ \exp\left[-(x - vt)^2/4Kt\right]$$

where

C	concentration of tracer
A	cross sectional area of channel
t	time after introduction of tracer or pollutant
x	distance from point of origin
$\bar{v}$	mean velocity of the stream
K	overall coefficient of diffusivity
M	initial mass of tracer

This equation describes the dispersion of diffusible matter about a point which moves with the mean speed of fluid flow. The distribution is symmetrical and Gaussian with respect to x at fixed values of t.

Pritchard [1954] and *Kent* [1955] have derived equations for the behavior of diffusible pollutants in estuaries yielding the general equation

$$\frac{\partial \bar{q}}{\partial t} = -V\frac{\partial \bar{q}}{\partial x} + \frac{1}{A}\frac{\partial}{\partial x}\left(AK_q\frac{\partial \bar{q}}{\partial x}\right)$$

where

$\bar{q}$ mean concentration of pollutant
K_q horizontal eddy diffusivity
S initial mass of pollutant

Only when the estuary is of uniform cross section, constant net velocity and constant eddy diffusivity is there an exact known solution.

Their solution under these conditions

$$q = S/2A\sqrt{\pi K_q t}\exp\left[-(x - \bar{V}t)^2/4K_q t\right]$$

gives the same equation as that derived by Taylor.

The experimental results of Taylor, Kent, and Pritchard show that the tracer behaves as predicted by the equation. The center of mass of the tracer moves with the speed equal to the mean velocity of the water and the tracer is dispersed both upstream and downstream from the center of mass such that the concentration-space distribution of the tracer is symmetrical and Gaussian. This means then that the movement of the center of mass of the tracer is a measure of the mean velocity of the stream.

Unfortunately space-concentration curves cannot be readily determined in large scale field studies as this would involve a large number of sampling stations and simultaneous sampling at each station at frequent time intervals. The procedure in the field has been to determine the time-concentration distribution as this requires only two or three sampling points, and to use some parameter of this distribution (mode, median, mean, range) as a measure of the mean velocity of the stream.

Pritchard [1954] has observed that the modal and mean values of time-concentration curves occur at much earlier times than given by the modal value of space-concentration curves. This becomes apparent when looking at a series of space-concentration curves in relation to a fixed point. A curve which has its maximum at an earlier station may have a concentration greater at the point in question than when the space-concentration curve shows a maximum at the point in question. This would be particularly true for the condition of very large values of the eddy diffusivity coefficient as the space-concentration curves would then flatten very rapidly as they were displaced downstream. Thomas has indicated that the centroid of the time-concentration curves obtained in his studues gave good agreement with the mean flow time or 'theoretical' detention period, that is, channel volume divided by discharge, for the reaches measured.

When one or more of the parameters (velocity, cross-sectional area, or eddy diffusivity) are functions of x, then the space-concentration curve is no longer Gaussian and symmetrical. Consider the case in which the eddy diffusivity is a linear function of x with increasing values of K_q in a downstream direction. The lower leg of the space-concentration curve will be subjected to a greater diffusion influence than the upper leg and as a result the curve will become skewed. The value of the center of mass of the curve will shift from that of the peak value. This will also affect the shape of the time-concentration distribution curve and the centroids of such distribution will fall further from the centers of mass of the space-concentration distribution than in the previous case.

It is interesting to observe Pritchard's equation under the conditions of linear variation of K_q with x. With uniform cross-section the equation may be written

$$\frac{\partial q}{\partial t} = \left(\bar{V} - \frac{\partial K_q}{\partial x}\right)\frac{\partial q}{\partial x} + K_q\frac{\partial^2 q}{\partial x^2}$$

The first term now becomes the mean velocity of the center of mass of the diffusant and includes

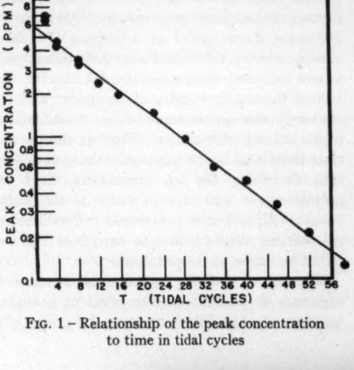

FIG. 1 – Relationship of the peak concentration to time in tidal cycles

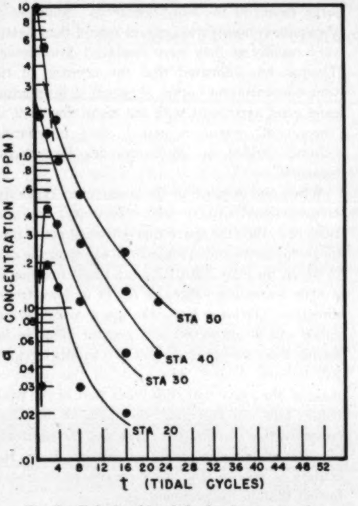

FIG. 2 – Relationship of the local concentration to time in tidal cycles for stations above the release point

a term in K_q as well as the mean velocity of the stream. Under the condition that K_q increases with x it becomes evident that increasing values of K_q in a downstream direction reduces the effect of the mean river velocity in transporting materials downstream. That is the pollutant moves with a mean velocity somewhat less than that of the water.

Such behavior is actually shown to occur in the estuary studies, made by *Pritchard* [1954] using the Delaware River model at Vicksburg. In these studies, which are described more fully below, peak values of the space-concentration curves lag behind the center of mass of the tracer and the center of mass of tracer lags behind the calculated mean velocity of the water. Since at the present time there is no known solution to the above equation describing the lag phenomena, field experiments are necessary in order to determine values of K_q and other parameters and mechanical calculations must be used to determine the distribution curves of the pollutant.

The existence of this lag phenomena makes it necessary to account for the effect of changing intensity of eddy-diffusivity along the course of a river when planning or interpreting field tests made to determine flow times.

Travel time in estuaries—In contrast with flowing streams, where the predominant motion is the down river flow in response to gravity, the waters of tidal estuaries are caused to circulate by forces of tide, wind, and density gradients as well as by the river inflow. Materials which find their way into tidal estuaries circulate with the water and are gradually diminished in concentration and flushed away. The time for a contaminant to be moved out of an estuary or at least out of one section of it, is ordinarily referred to as flushing time rather than travel time.

Estuarial circulation and flushing have been studied intensively by oceanographers for a period of about ten years. In the late 1940's *Ketchum* [1949, p. 64, 1950, 1951ab, 1955] attacked this problem and has since published numerous articles dealing with travel time and the dispersion of pollutants in estuaries. Ketchum's work is based on the hypothesis that the effective mixing length in an estuary is equal to the mean distance traveled by a water particle on the flood tide. Determination of this distance involves dividing the estuary into segments so related that the volume of each

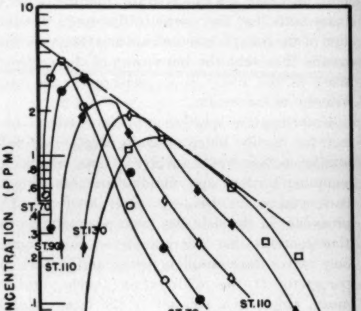

FIG. 3 – Relationship of the local concentration to time in tidal cycles for stations below release point

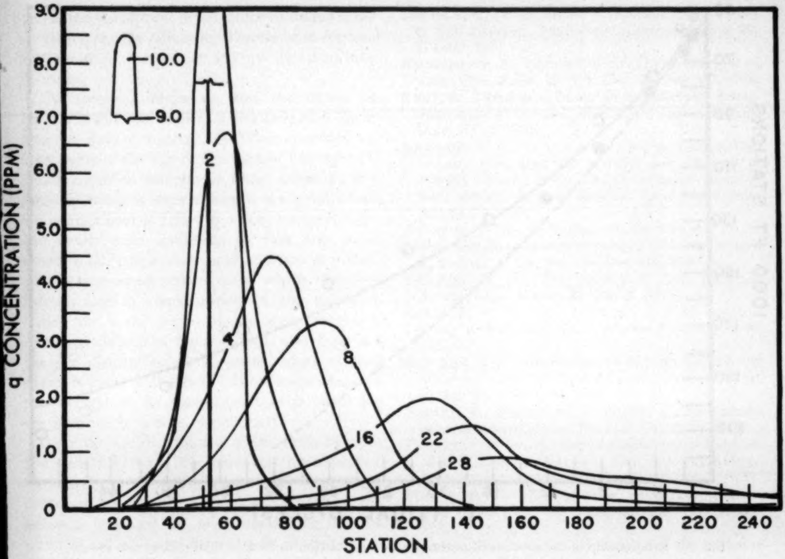

FIG. 4 – Longitudinal distribution of contaminant after designated number of tidal cycles

segment at low tide is equal to the volume of the next upstream segment at high tide. Although the method is empirical it has been found to produce results that are in good agreement with observed salinity gradients in portions of a variety of estuaries.

Stommel and *Farmer* [1952], *Arons* and *Stommel* [1951], and *Stommel* [1953] used a somewhat more sophisticated mathematical approach based on differential equations for continuity and for salt-transfer or diffusivity. The resulting differential equation is the same as that used by Pritchard. It was found that data from actual salinity surveys plotted well upon one or another of the family of curves predicted by the theory. However, the method provided no *a priori* method of predicting what the situation might be in absence of actual measurement.

Pritchard [1954] as mentioned above, investigated the travel time or flushing rate in a model of the Delaware River constructed by the Corps of Engineers at the Vicksburg laboratory. This model, which covered the reach from Trenton to the Capes, had scale ratios of 1 to 1000 horizontal and 1 to 100 vertical. Vertical metal strips imbedded in the concrete provided the degree of turbulence necessary to produce at all river flows in the model, the salinity gradients observed in the prototype.

The tests reported by Pritchard were made by injecting slugs of dye at various points in the estuary and observing the concentration of the dye at a large number of stations over many tidal cycles.

The peak concentration declined very rapidly during the first two tidal cycles and then fell away along a semi-logarithmic die-away curve (Fig. 1). The variations in concentrations with time at fixed points upstream and downstream from the point of contamination appear in Figures 2 and 3. The dye was introduced and all measurements of concentration were made at high water slack. Figures 2 and 3 do not show directly the distribution of the dye at any tidal cycle, but merely record the amount of dye at a given station on a given cycle. For example, the peak concentration at Station 150 occurred on the 22nd cycle and was 1.3 ppm. At this time the point of highest concen-

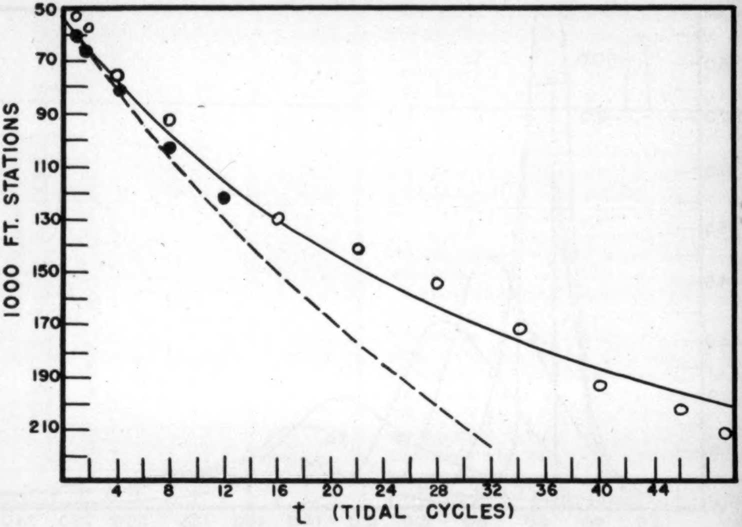

FIG. 5 – Relationship of the movement of the peak concentration to time in tidal cycles; also shown (broken curve) is the calculated net downstream water movement based on river inflow

tration in the estuary was 1.9 ppm at Station 140. On the 28th cycle the concentration of 0.9 ppm at Station 150 represents the true peak of the distribution curve for the dye. A better picture of the situation with regard to location of the dye may be obtained from Figure 4 which shows the concentration throughout the estuary at fixed times. The remarkable Gaussian normality of the distribution is evident in Figure 4. The very rapid initial decline in peak concentration during the first two tidal cycles is probably due to improper scale ratio for the local turbulence. Intense local turbulence occurred in the model around and in the lee of the vertical plates installed to produce in the model the general pattern of tidal action and salinity gradient observed in the prototype.

Figure 5 shows the downstream movement of the peak of the distribution curve. This peak lags appreciably behind the net average downstream movement of the inflowing river water. The reason why the dissolved material moves downstream more slowly than the water is explained by the equations already presented.

Since the differential equation cannot be solved mathematically, recourse must be had to experimentation in order to evaluate the parameters and apply the theory. This has been done by *Kent* [1955] in a dissertation which will soon be published.

Field measurements using slugs of tracers to determine the travel time and mixing in an estuary involve many severe difficulties in addition to great labor. It appears, therefore, that construction of a model provides the only reasonable approach to solution of such problems insofar as estuaries are concerned. Models are of course expensive. Once built, however, they are useful for many studies of economic importance other than the determination of flushing times. Enough work has already been conducted with models to indicate their reliability. Their successful use depends on the availability of the information necessary to confirm their behavior. In brackish-water estuaries, field measurements of salt concentration gradients over long periods involving different sequences of river flows provides the necessary data. In fresh-water estuaries as in rivers there is no alternative to tracer studies. These must be conducted in sufficient detail either to evaluate the coefficient of eddy diffusivity directly or to confirm a model in which more detailed investigations may be made.

The foregoing discussion and the curves of Figures 1 to 5 for studies on the Delaware River apply to slugs of contaminant. What is needed are predictions of the age distribution of the material which occurs in samples of water taken at any place upstream or downstream from a point where the contaminant is added as a continuous stream. For steady state conditions of river flow, tidal range, wind, temperature, and addition of pollutant, a time-concentration curve which describes the increase in concentration of the pollutant during the initial period of rise after starting a constant addition of the pollutant, also describes the age distribution in a sample taken at that point. A curve of this type has the same shape as the integral of the time-concentration curve for the addition of a slug of pollutant.

Once the age distribution of the radio-isotopes in a sample is known it becomes possible to predict the amount which should be found or through difference between the amount predicted and the amount measured to learn something of the physical and biological detention along the path of flow. This would be exceedingly valuable information in connection with pollution and self purification studies. It is unlikely, however, that detention can ever be estimated with sufficient accuracy that measurement of the downstream residue from a continuous discharge could be used to calculate time of flow of radioactive wastes in rivers and estuaries. Tracer tests supplemented by model studies remain the only tools for determining travel time of radioactive wastes in natural waters.

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Tracing Moisture Movement in Slick-Spot Soils with Radiosulfur: Part I*

J. V. JORDAN, G. C. LEWIS, AND M. A. FOSBERG

Abstract—Preliminary greenhouse tests using slick-spot soil and associated soil in columns indicated that cobalt^{60} and sulfur^{35} moved through the soil columns and appeared in the first drainage water. The first field experiments were run south of Boise on the Sebree-Chilcott associated series. Radiosulfur was used in the form of dilute sulfuric acid soaked into absorbent cotton. Each wad was specifically placed in or adjacent to a slick spot. After several months, soil samples from these tagged slick spots indicated that some characteristic water movement had occurred. Improved techniques have been developed and the study will expand to include slick-spot soils in irrigated and dryland areas.

Introduction—In the irrigated areas of southern Idaho there are estimated to be 300,000 acres of slick-spot soils. These are solonetz-type soils in the Sierozem great soil group and are represented here by the Sebree and the associated Chilcott series. The Sebree series of slick-spot soil is characterized by poor structure and poor water penetration caused by a deflocculated condition caused by a high sodium content. These slick spots vary in size from two feet to more than 50 in diameter and may represent from 10 to 50 pct of the landscape. During the past 25 years these soils have resisted all known methods for soil improvement. About three years ago the Idaho Agricultural Experiment Station launched a systematic study of the morphological, chemical and physical characteristics of slick-spot soils.

Preliminary studies have indicated that soil-moisture movement in and around slick spots may be one of the factors contributing to the formation of, and apparent permanence, of slick spots in soils. Nothing was known concerning the nature or extent of this moisture movement. In order to obtain such information, radioactive tracers were used to study the moisture movement. Methodology in this procedure is the principal objective of this report.

Literature review—There are relatively few references in the literature concerning the use of tracers for determining surface or subsurface movement of water. ***Putnam*** and others [1954] used the tracer, scandium^{46}, to determine underwater movement of sand and silt. These experiments are concerned with river siltation and the offshore movement of sand on the sea-bed. ***Jefferson*** and others [1953] employed sodium^{24} for finding leaks in sections of buried water mains up to five km in length. ***Rogers*** and ***Schilberg*** [1951] determined the initiation of convective flow through porous media by detecting counting rate changes in water dispersed throughout a bed of granular solids. Phosphorus^{32} was the tracer used. ***Kimura*** and ***Ikeda*** [1951] used radium^{224} to measure the flowing velocity of water through pipe. ***Inose*** and others [1955] have studied techniques for determining littoral drift.

Materials and methods—The first problem was to find a suitable tracer, preferably one which would fit into the existing analytical program. Sulfur^{35}, a soft beta emitter with a half-life of 87.1 days, was the first selection, since sulfate was one of the anions being determined in the chemical study. Cobalt^{60}, a gamma emitter with a half-life of 5.3 years, was the second choice. These isotopes were first used in a greenhouse experiment. Soil columns were set up in steel cylinders, 18 inches tall by nine inches diameter. Each cylinder was filled with the soil representing a particular horizon of the Sebree slick-spot soil and the Chilcott associated soil. These were prepared in duplicate, one set receiving sulfur^{35} and the other set cobalt^{60}. A depression about $\frac{1}{2}$ inch deep was made in the center at the soil surface of each cylinder and into the depression was poured one milliliter of solution carrying either sulfur^{35} as H_2SO_4 or cobalt^{60} as $CoCl_2$. The amount of activity in each case was about one millicurie. The soil cylinders rested on drainage plates so that drainage could be collected. Measured amounts of water were added to the soil cylinders every day so that the surface never dried out. All drainage was tested each week for radioactivity. However, in each case it was important to catch the first drainage from each cylinder to determine whether the tracer was in the soil moisture

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* Idaho Agricultural Experiment Station Research Paper No. 427.

TABLE 1 – *Description of soil horizons used in greenhouse experiment*

Soil	Depth	Cylinder	Description
	inch		
Sebree slick-spot soil	2–8	20, 26	B_2 horizon: weakly prismatic to fine blocky, silty clay loam; strongly plastic and sticky when wet, with slow permeability.
Sebree slick-spot soil	12–18	17, 18	B_3 horizon: moderately blocky, silt loam, high in clay; plastic and sticky when wet with moderately slow permeability, containing salt crystals.
Chilcott associated soil	0–4	1, 2	A_2 horizon: fine vesicular, coarse silt loam; very weakly plastic and sticky, and moderately permeable.
Chilcott associated soil	10–16	7, 5	B_2 horizon: strongly prismatic and blocky, silty clay loam; very sticky and plastic when wet, with moderately slow permeability.
Chilcott associated soil	19–21	22, 23	B_2 horizon: weakly blocky, silt loam high in clay; plastic and sticky when wet, with moderately slow permeability.

TABLE 2 – *Movement of radiosulfur and radiocobalt through Sebree and Chilcott soil horizons*

Date of drainage	Specific activity of residue (counts/minute/mgm residue)									
	S^{35} cylinders					Co^{60} cylinders				
	1	7	22	17	20	2	5	23	18	26
4/2	..	..	..	..	..	tracer added				
4/5	tracer added					..	..	..	..	..
4/19	60	57	40	[a]	[a]	76	70	59	[a]	[a]
5/2	245	41	178	1	[a]	800	750	10	5	[a]
5/12	111	5	5	380	[a]	1560	1490	290	1320	[a]
5/20	58	40	24	42	[a]	[b]	[b]	[b]	[b]	[b]
6/1	47	119	27	318	2	..	..	..	..	50
6/20	26	224	4	35	50	..	..	..	..	1250
7/21	163	128	[a]	..	64	..	..	..	..	1670

[a] No drainage.

[b] Experiment suspended.

front. An aliquot of the drainage was evaporated to dryness, weighed and the specific activity determined. Data for this preliminary experiment are presented in Tables 1 and 2.

Data in Table 2 show that both radiosulfur and radiocobalt moved through the soils continuously with the moisture. The experiment using cobalt^{60} was soon discontinued in favor of sulfur^{35}. Sulfur^{35} was a more convenient isotope to transport and to work with in the field and laboratory.

On the basis of this information, field work on slick spots in the dry range land near Boise, Idaho, was started. In September 1955 slick spots were selected. One millicurie of sulfur^{35} in H_2SO_4 was placed in a specific position in or outside each slick spot as shown in Figures 1–7. Procedure for this application began in the laboratory and consisted of pipetting a one milliliter aliquot of the tracer solution into a small glass vial. This volume of solution contained one millicurie of sulfur^{35}

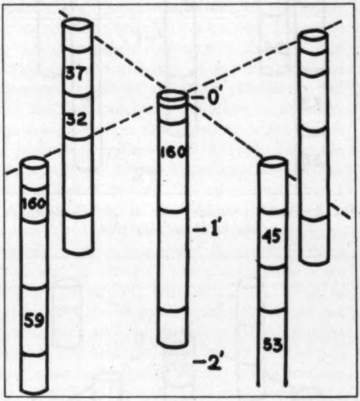

FIG. 1 – Spot A; outside spot on surface, May 1956

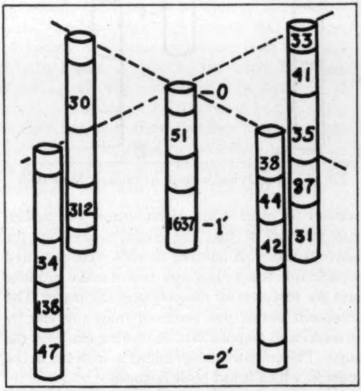

FIG. 2 – Spot B; outside spot, at 12-inch depth below B_2, above lime hardpan, May 1956

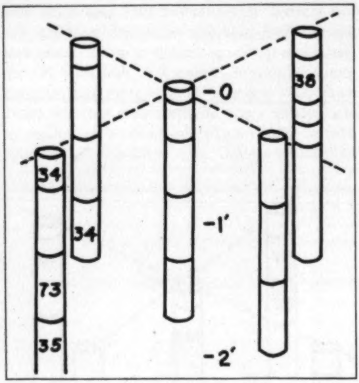

FIG. 3 – Spot C; outside spot, at 18-inch depth on lime hardpan, May 1956

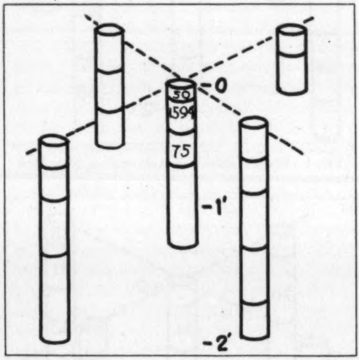

FIG. 4 – Spot 1; inside spot, at surface, May 1956

activity. A piece of absorbent cotton was pushed into the vial so that the cotton soaked up the active solution. A number of vials were prepared for field use. A soil auger was used to make entrance into the test sites for placement of the tracer. The absorbent cotton was removed from the vial by tweezers and dropped into the boring made by the auger. The soil borings were filled in with soil in the order in which it had been removed.

In May 1956 the slick-spot sites were sampled. From September 1, 1955 to May 31, 1956 the average precipitation was 11.47 inches according to U. S. Weather Bureau records taken three miles to the north. Certain sites were sampled again in August. From May 1 to August 31, 1956 the average precipitation was only 1.94 inches.

The tagged slick spots were sampled using a Kelley core sampler taking four-inch undisturbed soil core. In May, each tagged spot was generally sampled in five positions. These were as follows: Down through the profile along the vertical axis of original placement of the tracer; then cores re-

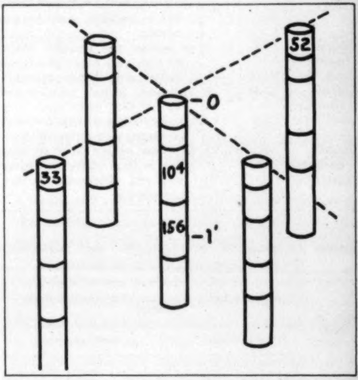

FIG. 5 – Spot 2; inside spot, at 11-inch depth, below B_2, August 1956

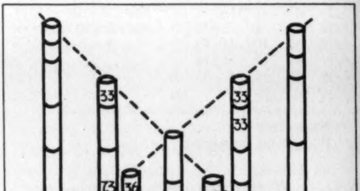

FIG. 6 – Spot 3; inside spot, at 29-inch depth, on top of lime hardpan, May and August 1956

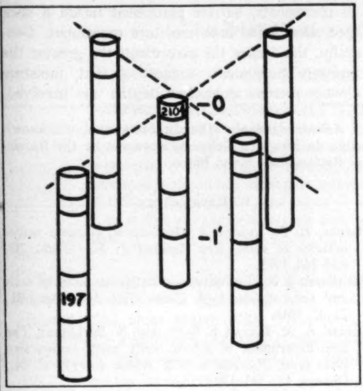

FIG. 7 – Spot 4; inside spot on surface, August 1956

moved one foot to the north, south, east and west of this central axis. Soil samples were taken from the various horizons. Precautions were taken to avoid cross-contamination of samples by stripping off the outer inch of soil from the soil cores. The samples were air-dried and kept for physical and chemical analyses. In August some spots were sampled at a two-foot radius from the central axis. Radiosulfur determinations were run on an aliquot from the ammonium acetate extraction procedure [*Hosking*, 1948]. Barium sulfate was precipitated in the aliquots, filtered by suction on stainless steel filters through a one-inch diameter No. 42 Whatman filter paper. The filter disc was dried and the activity measured in an RCL preflush flow counter using Q-gas. On the basis of the soil sample and aliquot taken, a specific activity was calculated as counts per minute per gram of soil. These values were posted on the diagrams illustrated in Figures 1 to 7. Natural radioactivity existing in these soils and present in the ammonium acetate extract was determined and this background activity was found to average 30 counts per minute per gram of soil. Various workers have reported on the existence of natural radioactivity in soils. *Gibbs* and *McCallum* [1955] indicated that soil radioactivity depends partly on the rock materials from which the profiles were developed. Consequently, values of 30 and less are disregarded in these data. However, this does not imply that the added tracer did not move into those soil zones but suggests that the methods of measuring the sulfur^{35} activity were not sufficiently precise.

Vegetation samples, principally from sagebrush growing outside the perimeter of slick spots, were collected. Many samples contained considerable radiosulfur but so far it has not been determined whether the tracer had been absorbed by the roots penetrating into the slick spot or absorbed after the tracer had moved out.

Results and discussion—Results of the tracer movement shown in Table 2 are directly related to the soil descriptions presented in Table 1. Soil texture and the stability of soil structure are important factors in soil water movement. Not until the sixth week after moisture applications began did the water finally penetrate the Sebree B_2 horizon in cylinders 20 and 26. However, radioactivity was present in the first drainage from these cylinders and all the others in Table 2.

An examination of the soil core diagrams in Figures 1 to 7 reveals that the tracer did move from the point of placement in certain patterns which may be assumed to be characteristic of the moisture movement. Obviously, there was no correlation between moisture content of the soil core samples and the specific activities of these samples. The determinations were run at the time of sampling so the specific activity values posted in the soil cores indicate the path of moisture movement from the tracer placement only.

In Figure 1, slick-spot A, the activity was placed just outside the spot, at a depth of about three inches. The May samplings indicate that moisture had moved downward and away from the slick spot. In Figure 2, spot B, the tracer had been placed outside the slick spot at a depth of 12 inches; that is, below the B_2 horizon but on top of the lime hardpan. Here the data show that the moisture moved upward to the surface and toward the slick spot but, as in Figure 1, the downward movement was away from the slick spot. In Figure 3, spot C, the tracer was placed outside the slick spot, 18 inches deep on the lime hardpan. In this instance, the greatest movement tended to be away from the spot. However, there was lesser movement upward toward the spot.

In Figure 4, spot 1, the tracer was placed in a slick spot but near the perimeter and on the surface. The only apparent movement here was slightly downward. However, a sagebrush sample collected outside the spot contained radiosulfur indicating there had been surface erosion and some surface runoff from inside the spot to the outside.

Figure 5, spot 2, illustrates the movement when the tracer was placed inside the spot but near the perimeter, 11 inches deep, below the B_2 horizon. The principal movement was upward further into the spot. There was lesser movement toward the outer edge. This spot was sampled in August. Figure 6, spot 3, was sampled in May and August. The August samples were taken on a 24-inch perimeter. Here the tracer had been placed inside the slick spot, 29 inches deep on top of the lime hardpan. The May samples indicated that the movement was upward and outward in all directions from the point of placement. The August samples showed that no movement took place at least as far as the 24-inch perimeter during the summer months, during which the average precipitation was only 1.94 inches.

In Figure 7, spot 4, the tracer had been placed on the surface and the spot sampled in August on a 12-inch perimeter. Results showed that the main movement was downward.

Conclusions—Results of this experiment indicated that radiosulfur is a suitable tracer for studying moisture movement in slick-spot and associated soil. This information may then lead to the understanding of slick-spot formation, and ultimately control and eradication practices.

Under the conditions of the experiment where precipitation was only about 11.5 inches, the tracer moved from the point of placement in definite directions, depending on the placement. Preliminary experiments had shown it reasonable to assume that the tracer moved with the soil moisture.

Where the tracer was placed outside the slick spot, at depths below the surface, the moisture moved both downward away from, and upwards toward, the slick spot. Where the tracer was placed inside the slick spot at depths below the surface, the moisture movement was upward. Of all placements, surface placement inside a slick spot showed the least moisture movement. Generally, the deeper the placement, the greater the moisture movement, suggesting that moisture already present at shallow depths was involved.

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The Distribution of Radioactivity from Rain

LLOYD R. SETTER AND CONRAD P. STRAUB

Abstract—Under conditions similar to Cincinnati, Ohio, fallout is the result of rainout and snowout. Without precipitation there is little fallout even though the particulate activity of surface air is abnormally high. Much of the suspended activity in cistern water from rain will be removed by sedimentation. Over 90 pct of both the suspended and dissolved fallout becomes associated with soil and vegetation rather than appearing in surface waters. From the spring of 1953 to January 1957, the fallout of strontium^{90} (Y^{90}) in Cincinnati, Ohio, is estimated to be at least ten and probably not more than 30 millimicrocuries per square meter of surface area.

Fallout measurements, largely as precipitation, have been made on a continuous basis at Cincinnati, Ohio, since March 1953. The studies of 1953 [*Nader* and others, 1954] and 1954 [*Setter* and *Goldin*, 1956] were implemented in October 1953 by weekly or daily tests of the atmospheric particulate activity and by the operation of an experimental cistern near the site of the rain collector. Correlation is now possible between air-particle concentration and rainout (washout by precipitation) and distribution of activity between the separated solids and the supernatant liquid in the cistern liquid can be determined. This report includes data relating to activity levels in air particulates, rainfall, and certain Ohio rivers.

Methods—The methods of sample collection have been described [*Setter* and *Goldin*, 1956]. The precipitation values reported in Figures 1 and 2 are the means of values reported for six stations and were obtained from U. S. Weather Bureau climatological data. To compensate for differences in hours of collection some adjustment in these values was made.

Rainfall was collected in a pail-type sampler. Aliquot samples were filtered through membrane filters and the filtrates evaporated. The gross beta-gamma activity of the filter and dissolved solids was measured, and the results reported on an area basis. Repeat measurements on many samples were made to establish the decay rates of suspended and dissolved activities. When combined the suspended and dissolved activity usually exhibited an exponential negative decay rate of from 1.0 to 1.2 for known dates of bomb tests. For tests of unknown origin appropriate dates were selected to conform in general to this rate of decay.

The air-particulate activity of samples from January 1, 1955, to August 1956 was determined from swatch sub-samples representing roughly 80 m^3 of air filtered through glass fiber filters over a 24-hour period from the Lincoln Park area, Cincinnati [*Tabor*, 1956]. Continuous air sampling was initiated August 1, 1956. Air activity was obtained daily (except week-ends) by filtering 20 to 30 m^3 of air through a membrane (cellulose acetate) filter. Week-end samples were collected after one to three days. The membrane filter sample was placed in an aluminum dish, saturated with 95 pct alcohol, ignited, flash flamed with a Meeker burner, and counted for two 8-min. periods in an internal proportional counter. The beta counting was usually postponed for two days after collection to prevent the interference of short-lived naturally-occurring alpha and beta activity [*Setter* and others, 1957].

Precipitation, air particulate, and fallout activity—The results of precipitation in inches, air particulate activity in micromicrocuries per cubic meter ($\mu\mu c/m^3$), and the fallout activity in millimicrocuries per square meter ($m\mu c/m^2$) have been summarized in Figures 1 (1955 data) and 2 (1956 data). From the decay-of-rain samples the age of the activity was estimated and is shown for most of the samples in the legends of Figures 1 and 2. The rate of decay is plotted as broken lines.

Considering the particulate activity in air from stations in the Midwest (Cincinnati, Louisville, St. Louis, Chicago, Minneapolis, and Detroit) the average background level of approximately 0.05 $\mu\mu c/m^3$ in the fall of 1953 has increased to an arithmetic average level of 0.6 $\mu\mu c/m^3$ in 1954, 1.55 $\mu\mu c/m^3$ in 1955, and 2.26 $\mu\mu c/m^3$ in 1956. During continental tests in 1955, the activity in Cincinnati air (Figure 1) fluctuated from a high of 10 $\mu\mu c/m^3$ of rapidly decaying radioactivity to a low of 0.88 $\mu\mu c/m^3$. Due primarily to the more distant bomb-test areas and the consequent dispersion of activity and decay of short-lived iso-

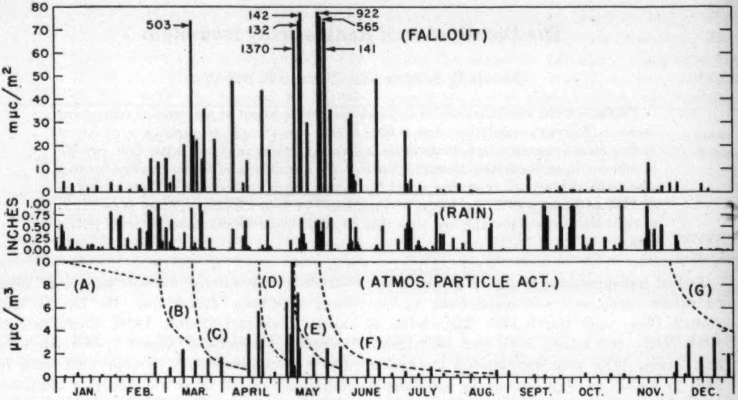

FIG. 1 – Radiation levels, air and rainfall, 1955; (A) June 4, 1954, decay slope (ds) 1.0; (B) Feb. 18, 1955, ds 1.2; (C) March 12, 1955, ds 1.0; (D) April 15, 1955, ds 1.2; (E) May 5, 1955, ds 1.2; (F) May 15, 1955, ds 1.2; (G) November 5, 1955, ds 1.0

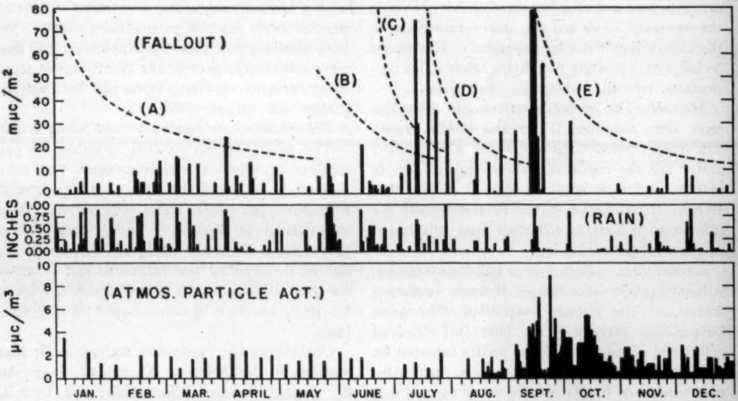

FIG. 2 – Radiation levels, air and rainfall, 1956; (A) December 1, 1955, decay slope (ds) 1.0; (B) May 3, 1956, ds 1.0; (C) June 13, 1956, ds 1.0; (D) July 10, 1956, ds 1.0; (E) August 27, 1956, ds 1.0

topes there was less fluctuation in radioactivity levels (8.9 to 0.58 μμc/m³) during the Pacific and foreign tests of 1956. However, a higher sustaining level of air radioactivity was noted for the entire year.

Fallout from 15 rain collections made between March 15 and June 25, 1955 showed activity levels above 30 mμc/m², with the level in seven of these varying from 141 to 1370 mμc/m² (Fig. 1). Most of this activity was short-lived as shown in the decay curves. Relatively little radioactivity was observed in samples collected during the first two and last six months of 1955, but the activity collected was of longer half-life. Although the air was relatively active in December, precipitation and consequently the fallout was insignificant.

In 1956 (Fig. 2) the radioactive fallout in excess of 10 $m\mu c/m^2$ was common throughout the year. During this time air activity was moderately low (less than 3 $\mu\mu c/m^3$) except in September and October. The decay curves show that most of the fallout activity in 1956 was longer-lived than that collected in 1955.

A somewhat better appraisal of the amount of long-lived radioactive fallout may be obtained by considering the cumulative residual deposition. At Cincinnati, and presumably at all non-arid areas several hundred miles removed from the weapons test site [*List*, 1956], increased radioactive fallout appears to be associated with periods of rainfall and snowfall.

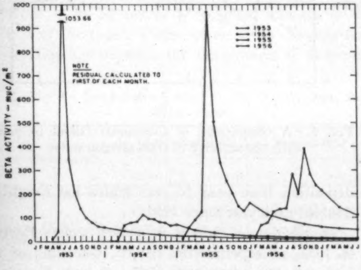

FIG. 3 – Residual fallout

The radioactive fallout, identified quite precisely as to age and rate of decay for the more radioactive samples and less accurately for the low-level radioactive samples, has been extrapolated to the first of each succeeding month. The cumulative residual activity in $m\mu c/m^2$ of Earth's surface, assuming no loss, is plotted as shown in Figure 3 for each of the four years of record from April 1953 to July 1, 1957. In each year there is a peak of activity during or immediately following test operations. High peaks of 1054 $m\mu c/m^2$ on June 1, 1953 and 970 $m\mu c/m^2$ on June 1, 1955 are shown for the two years of continental tests (1953 and 1955), whereas longer-lived peaks of 110 and 390 $m\mu c/m^2$ were observed on July 1, 1954 and October 1, 1956, respectively. Fallout during the latter periods was from Pacific and foreign test operations. The yearly deposition of observed fallout was extrapolated to one-year-old fission products.

One-year-old mixed fission products contain 3.9 pct strontium^{90} (yttrium^{90}) according to *Hunter* and *Ballou* [1951]. This value was used to cal-

TABLE 1 – *The distribution of fallout in cistern water*

Series	Date of accounting	Precipitation no.	Ext. date[a]	Age of bomb debris	Total precip.	Gross beta radioactivity					
						Recovered in cistern	In rain	In cistern water		In cistern water	
								Dissolved	Suspended	Dissolved	Total
1	2	3	4	5	6	7	8	9	10	11	12
	1955			day	inch	μc	μc	pct.	pct.	μμc/l	μμc/l
1	Mar. 4	19	Mar. 8	19–300	6.34	2.86	1.40	14	77	69	445
2	Mar. 16	5	Mar. 19	7– 30	1.37	10.00	9.71	53	22	4160	5890
3	Mar. 21	4	Mar. 22	10	1.96	1.02	0.95	30	17	163	256
4	May 5	16	May 11	20– 55	2.79	1.46	2.15	46	13	262	337
5	May 17	6	May 26	15	1.59	3.48	7.16	28	12	660	950
6	June 21	14	June 29	37	4.62	8.02	8.60	38	33	720	1340
7	July 14	11	July 20	60	3.68	1.56	2.07	56	1	259	263
8	Aug. 24	16	Aug. 26	101	3.07	0.36	0.28	26	7	34	43
9	Sep. 28	6	Oct. 4	136	3.50	0.15	0.34	49	7	22	25
10	Oct. 25	11	Nov. 10	163	6.01	0.17	0.20	23	8	7	10
11	Nov. 18	6	Nov. 30	187	2.93	0.11	0.53	39	5	24	28
	1956										
12	Feb. 9	36	Feb. 9	64–270	9.32	1.16	1.14	56	34	76	123
13	Mar. 7	11	Mar. 7	36– 98	5.08	1.65	1.83	37	27	157	269
14	July 27	8	July 27	17– 44	2.08	4.14	4.66	19	23	410	908
15	Sep. 25	24	Sep. 25	15– 77	5.58	7.81	9.40	55	22	762	1070
1–15	Total	193			59.92	43.95	50.42	40[b]	25[b]	322[b]	524[b]

[a] All measurements in a series extrapolated for decay to this date.

[b] Weighed average.

culate the combined activity of $Sr^{90} - Y^{90}$ deposited for each of the four years as follows:

Year of deposition	One-year-old activity	Sr^{90}-Y^{90}
	mμc/m²	mμc/m²
1953	31.3	1.22
1954	37.5	1.46
1955	63.2	2.46
1956	150.4	5.87
Total 1953–56	282.5	11.0

Precipitation for each of the four years amounted to 22.9, 36.3, 44.7, and 41.8 inches, respectively, a total of 145.7 inches. On this basis the average activity of precipitation over the four-year period was 76.4 micromicrocuries per liter (μμc/l) of one-year-old fission product and 3.0 μμc/l of Sr^{90} (Y^{90}).

These levels in water appear insignificant, compared to the maximum permissible level of $Sr^{90} - Y^{90}$ in drinking water of 800 μμc/l [*U. S. National Bureau of Standards*, 1953]. However, it may be significant to observe the increase in the deposition from year to year which has roughly doubled each year since 1954.

Table 2 – *The radioactivity of Ohio surface water as compared to rainout*

Date of colection	Stream stations[a]	Stream water activity				Rain	Rainout[b]	
		Maximum		Average			Dissolved	Total
		Dissolved	Total	Dissolved	Total			
1956		μμc/l	μμc/l	μμc/l	μμc/l	inch	μμc/l	μμc/l
Jan. 17	A	19	42	6	23	2.5	50	150
Feb. 20	A	...	43	...	33	6.8	160	280
Feb. 28	B	80	141	52	99	1.2	100	490
Mar. 13	A	...	38	...	25	2.0	360	950
Apr. 17	B	38	54	29	46	3.7	...	830
Apr. 24	A	25	40	16	31	0.2	...	2120
May 14	A	64	87	43	67	1.2	...	620
June 6	B	29	50	10	30	4.6	140	360
June 18	A	30	66	23	58	1.1	420	760
July 25	B	45	79	44	62	5.0	...	2000
July 31	A	80	217	64	130	1.3	510	840
Aug. 15	A	51	140	32	80	0.6	1310	2040
Sep. 11	A	84	116	35	62	1.2	1420	2180
Sep. 19	B	89	178	57	105	1.7	2260	7000
Oct. 8	B	27	44	22	37	1.1	1320	3300
Oct. 23	A	30	158	20	51	0	...	...
Nov. 14	B	36	46	31	47	0.5	317	440
Nov. 26	A	60	68	39	47	0.6	...	478
Dec. 18	A	34	69	23	44	1.09	624	992
1957								
Jan. 15	B	26	42	20	38	1.42	193	2941

[a] Ohio State Board of Health data on: A, Little Miami River at Newtown and five stations on Great Miami River from river mile 24.8 to 96.6; and B, four stations on Scioto River from river mile 15 to 140.

[b] Weighted average activity of rain at Cincinnati collected between dates of stream sampling.

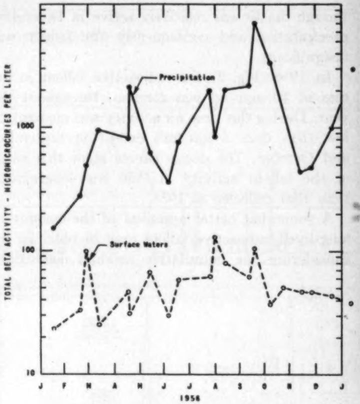

FIG. 4. – A comparison of Cincinnati fallout in rain with the activity of Ohio stream water

Distribution of fallout in cistern water—Early in 1954, an experimental cistern, consisting of a hopper-bottomed tank of 2.62 m³ capacity, was installed to collect precipitation from a portion of the roof of an abandoned home. The cistern was in operation from February 10, 1954 to March 7, 1956, and from July 5 to September 25, 1956. During this period, settled cistern water was withdrawn and tested at frequent intervals while the settled sludge was removed and tested on fifteen occasions. The more significant data from cistern operation are presented in Table 1. The total activity found in the cistern water, sludge, and sludge supernatant are indicated in Col. 7. Sludge supernatant consisted of a known quantity of cistern water (up to 50 l) used to wash the sludge from the cistern bottom. This water was then settled for 10 to 15 minutes and the supernatant removed from the sludge by decantation. The sludge contained loose shingle stone which had been washed into the cistern. It was separated from the sludge and samples of the supernatant, sludge, and roof stone were tested for beta radioactivity. The sludge and supernatant solids found in the roof drainage varied from 9 to 71 with an average of 30 ppm of dry solids of which 30 pct were volatile.

During the sixteen-month period of cistern operation, a total of 50.4 μc of beta activity (Col. 8) from bomb debris ten to 300 days old was estimated to be in the cistern rain. Of this total, 43.95 μc or 87 pct was recovered from the cistern. The remaining 13 pct represents activity fixed to the asphalt roof shingles and errors in measurement. Estimations based on the activity found on washed shingle stone separated from the cistern sludge accounted for much more than the 13 pct. However, since the stones tested were bathed in radioactive rain for days or weeks they may have adsorbed more activity than would shingle stones during roof runoff.

The soluble activity in the cistern water varied from 14 to 56 pct or a weighted average of 48 pct of the total. There seems to be no clear-cut relationship between the percentage of dissolved activity and the age of bomb debris. This is contrary to the observation made in 1953 [*Nader* and others, 1954] that the percentage of dissolved activity in the rain was less for activity of short half-life. Other factors, such as the presence of inert material in the fire ball, the abundance of local non-radioactive air pollutants, the time of exposure of radioactive particles to moisture, and possibly the inflow of radioactive contaminants of different chemical characteristics from the stratosphere to the rainout zone, probably play a role in forming the soluble fraction.

TABLE 3 – *Comparative beta activity of rain, cistern, and stream waters*

Series dates[a]	Dissolved activity			Total activity		
	Rain	Cistern	Streams	Rain	Cistern	Streams
	μμc/l	μμc/l	μμc/l	μμc/l	μμc/l	μμc/l
Nov. 18, 1955–Feb. 9	54	76	6	130	123	23
Feb. 9–Mar. 7	152	157	52	390	269	33–99
July 5–July 27	1430	410	44	2420	908	62
July 27–Sep. 25	800	762	32–64	1830	1070	62–130
Geometric means	311	247	28.4	689	424	54.8
Per cent removal compared to rainfall	...	20.6	91	...	38.5	92

[a] 1956 except as shown.

The concentration of dissolved activity in cistern water varied from 7 to 4160 or an average of 332 μμc/l. Lower values (less than 76 μμc/l) were observed during periods when the bulk of the activity was estimated to be older than 100 days, whereas for activity 7 to 98 days in age, the dissolved activity was 157 μμc/l or more. The percentage of activity associated with the suspended solids ranged from one to 77 pct, with an average of about 25 pct.

In summary, the cistern study reveals that slightly more than half of the activity found in the cistern water was soluble and that up to a third of the activity would be associated with the suspended solids. Over two thirds of the insoluble activity settles as a sludge (1.5 kg dry weight) having an activity of 10 μc/kg (dry weight). Septicity resulted in further solution of activity, but diffusion into the cistern water was minimal when the sludge was undisturbed.

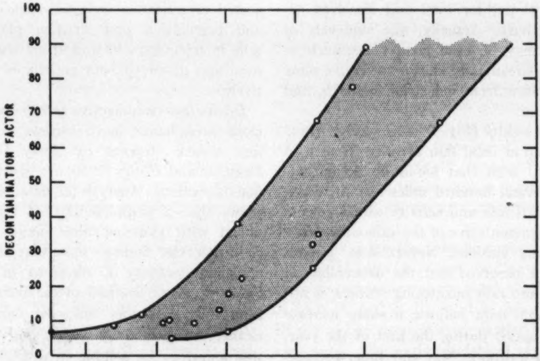

FIG. 5 – The decontamination of rain by natural agencies

The distribution of fallout in surface waters—Nine grab and seven composite (seven- to ten-day) samples from 13 stations on the Ohio River from Pittsburgh, Pennsylvania, to Louisville, Kentucky, were collected between December 27, 1955 to April 20, 1956 in a cooperative study with the Ohio River Valley Water Sanitation Commission. The maximum beta activity found was 100 $\mu\mu$c/l as compared to an arithmetic average value of 27.5 $\mu\mu$c/l of which 15 $\mu\mu$c/l was in solution.

Through the courtesy of F. H. Waring, Chief Sanitary Engineer, Division of Sanitary Engineering, Ohio State Board of Health, the results of additional samples collected from surface streams tributary to the Ohio River are included in Table 2 and Figure 4. The maximum average activity levels of the surface waters of the Little Miami, the Great Miami, and Scioto Rivers are compared with the SEC Cincinnati rainout results for collections made between river samplings.

The stream water results show a maximum dissolved activity of 89 $\mu\mu$c/l compared to a maximum total (suspended and dissolved) activity of 217 $\mu\mu$c/l for tests in 1956. The average total activity for each sampling date fluctuated from 25 to 130 $\mu\mu$c/l depending to some degree on the activity of the more recent rains. The yearly geometric average total and dissolved beta activity of stream water was 50 and 27 $\mu\mu$c/l, respectively, as compared to 974 $\mu\mu$c/l total and 389 $\mu\mu$c/l dissolved activity for Cincinnati rain. The average removal by natural agents is therefore 95 and 93 pct for total and dissolved activity, respectively. Actually, the removals of rain activity may be even greater inasmuch as some of these streams are known to receive some radioactive wastes from industrial, research, and medical facilities.

The plotted results (Fig. 4) more clearly define the relationship of total rain activity (from Cincinnati fallout) with that found at stream stations up to several hundred miles distant. Obviously, Cincinnati rain and activity measurements may not be representative of the rainout at some of these stream stations. Nevertheless, general trends may be observed and the desirability of establishing more rain monitoring stations is apparent. The rain data indicate a sharp increase (150 to 2100 $\mu\mu$c/l) during the first of the year, then, following a drop in May and June, a second rise to levels of 2000 to 7000 $\mu\mu$c/l by September. During the last three months of the year, the rain activity decreased. The lower levels of rain activity usually correspond to longer-lived bomb debris and high levels correspond to young (rapidly decaying) fission products.

The ratio of total rain activity to total surface water activity was determined for each month and reported in terms of the decontamination factor (rainout or fallout activity divided by the surface water activity). These decontamination values were plotted against the rain activity as shown in Figure 5. It will be seen that removal of radioactivity by natural agents increases with increased activity of the rain. Comparable in many respects with other pollutants, the plotted values indicate the application of the law of diminishing returns, that is, high decontamination factors in order of 65 to 90 (98.5 to 98.9 pct removal) for relatively young bomb debris and decontamination factors of 5 to 10 (80 to 90 pct removal) for lower-level longer-lived activity.

The Cincinnati rainout and cistern studies have been combined with the Ohio State stream data for comparison of the distribution of radioactive rainout. The rainout (corrected for decay to the end of a cistern sampling period), the cistern water activity of series 11 to 15 (Table 1), and the activity of stream waters of appropriate date are summarized in Table 3. The table shows that subsidence in the cistern and adsorption by roof shingles results in an average loss of 38.5 pct of the total and 20.6 pct of the dissolved rain activity, whereas the low activity found in stream waters indicates that radioactive particles adsorbed on surfaces, such as vegetation and soil, and percolation and dilution play important roles in achieving a 92 and 91 pct reduction of the total and dissolved beta activity of rain, respectively.

Discussion—Radioactive fallout has been under close surveillance since nuclear weapons were first tested. Reports by *Libby* [1956ab], and *Eisenbud* and *Harley* [1956] are based on gummed film collections. Analysis of data by *List* [1956] shows that a preponderance of the fallout obtained with gummed films occurs during precipitation. Our findings show that about one-half of fallout activity is dissolved in rain water. Similarly about one-half of the activity collected from dust collectors following Operation Hurricane, as reported by *Russell* and others [1955] was found to be soluble in distilled water and dilute salt solutions. The fraction of the total activity which is dissolved or soluble depends on many factors such as the age and particle size of the bomb debris and the adsorptive capacity of local atmospheric dust with which it comes in contact before or during rainout.

Although significant radioactive dustfall of the larger particles may occur in the vicinity of a nuclear test site the finer particles are removed from the air by rainout or snowout and, to a lesser degree, by the impingement of particles on leaves, grasses, and other solid surfaces by wind action. A comparison of the estimated $m\mu c/m^2$ of strontium fallout from rain collections at Cincinnati, Ohio, New York City, New York, [*Harley* and others, 1956], and Milford Haven, England [*Stewart* and others, 1956] is as follows:

Year of deposition	Cincinnati, Ohio	New York, New York	Milford Haven, England[a]
1953	1.22	...	...
1954	1.46	2.88	1.15[b]
1955	2.46	3.35	2.65
1956 (1st half)	2.8	6.67	0.5[c]
1956 (2nd half)	3.07	...	...

[a] The Milford Haven results (HP/R 2017) are reported in units 1000 times higher but the concentration in rain water and a subsequent discussion of these results (HP/R 2056) verifies the correctness of the $m\mu c/m^2$ unit.

[b] May through December.

[c] January through March.

Agreement in fallout values is surprisingly good for the three stations in 1954 and 1955. Disagreement of values for the first five or six months of 1956 may be expected from the known variations in weather patterns with respect to the presence of radioactive air masses prior to more uniform distribution with time. This was clearly demonstrated in Cincinnati during December 1955 when air activity was relatively high but, since no precipitation occurred, the fallout was negligible.

In order to determine the variation in fallout or its distribution over grazing or farm land many more collectors will be necessary. Many rain collectors should be satisfactory, such as the 13.5-inch bucket used, the eight-inch pot *Harley* and others [1956] used in New York or the 0.22 m^2 polyethylene funnel and bottle used at Milford Haven [*Stewart*, 1956]. In continuous use each will collect true dust-fall and secondary aerosols (from previous rainout) as well as rainout and snowout. Depending on wind protection the efficiency with which snow samples will be collected may vary. Studies at Cincinnati by *Nader* [in press] show that a polyethylene waste basket having a diameter of 7.75 inches was as effective in retaining dust as similar containers provided with baffles or wetted with water during periods when the rain had evaporated. The dry solids of rain became attached to the container. Since it is the rain which contains the significant radioactive fallout, this, or a similar container lined with a polyethylene bag, would be a simple and satisfactory fallout collector.

Because most of the activity does not appear in runoff it may be presumed that the radioactivity remains on solid surfaces such as grasses, crops, and soil where, although not presenting a significant external radiation field, it may, at greatly increased levels, present an internal exposure problem via the food chain.

Summary—Fallout radioactivity, largely as precipitation, has been monitored continuously at Cincinnati, Ohio, since the spring of 1953. Rain, cistern, and surface waters were tested to determine distribution and characteristics of the radioactivity.

During the two years of continental testing (1953 and 1955), the predominant air contaminants were characterized as young fission products. The deposition of activity from rain was variable and occasionally quite high. The monthly residual fallout (corrected for decay) reached a maximum of about one microcurie per square meter of surface area on June 1, 1953, and again on June 1, 1955.

In 1954 and 1956 when the air contaminants were of longer half-life the maximum monthly residual was about 0.1 $\mu c/m^2$ in 1954 and 0.4 $\mu c/m^2$ in 1956. It is estimated that on July 1, 1957, the residual activity from fallout during 1953, 1954, 1955, and 1956 was 10, 12, 50, and 105 $m\mu c/m^2$, respectively, or a total of 177 $m\mu c/m^2$ of fission products (nine months to four years of age). The strontium^{90} (yttrium^{90}) deposition at Cincinnati for the four years is estimated to be 11 $m\mu c/m^2$ or an average concentration in rain of 3 $\mu\mu c/l$.

Depending on the time of contact with water, the age of contamination, and other factors, a variable percentage of the total activity (average of 40 to 50 pct) is dissolved in rain water. About 40 pct of the total activity settles out from cistern water. The activity of local surface streams indicates that over 90 pct of the dissolved and total activity in the rain has been removed.

Somewhat less than half of the total activity in surface water was in a dissolved state.

Since so little of the rainout activity can be accounted for as runoff it may be presumed that the radioactive fallout is fairly firmly fixed near its point of deposition as particles or by adsorption on solid surfaces such as vegetation and soil.

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Uranium and Radium in the Ground Water of the Llano Estacado, Texas and New Mexico

F. B. BARKER AND R. C. SCOTT

Abstract—Water samples were collected from 47 wells and springs in the Ogallala formation in the Llano Estacado section of the High Plains, Texas and New Mexico. The Ogallala, a fluviatile geologic terrane, is hydrologically and geologically isolated in this region, therefore, the observed radiochemical concentrations are considered as inherent characteristics of the formation in this area. The uranium concentrations ranged from 0.9 to 12 parts per billion (ppb) (median 6.2 ppb), and the radium concentrations ranged from < 0.1 to 0.8 micromicrocuries per liter (median 0.1 $\mu\mu$c/l). The uranium concentrations show a tendency to correlate with the gross chemical character of the waters in accordance with the expected chemical behavior of uranium. The departure of the radium-uranium ratios in all samples from radioactive equilibrium value is explained on the basis of carbonate-complexing of uranium and selective adsorption of radium by minerals having a capacity for base exchange.

Introduction—An investigation of the occurrence of uranium and radium in the ground water in the Ogallala formation in the Llano Estacado (Staked Plain) of Texas and New Mexico was made as part of a comprehensive investigation of the occurrence and history of radioelements in ground waters in various geologic terranes of the United States. A greater insight into the hydrogeochemistry of the radioelements is sought. Understanding the behavior of these elements may lead ultimately to their use in more intensive studies of some of the processes of ground-water geology and hydrology.

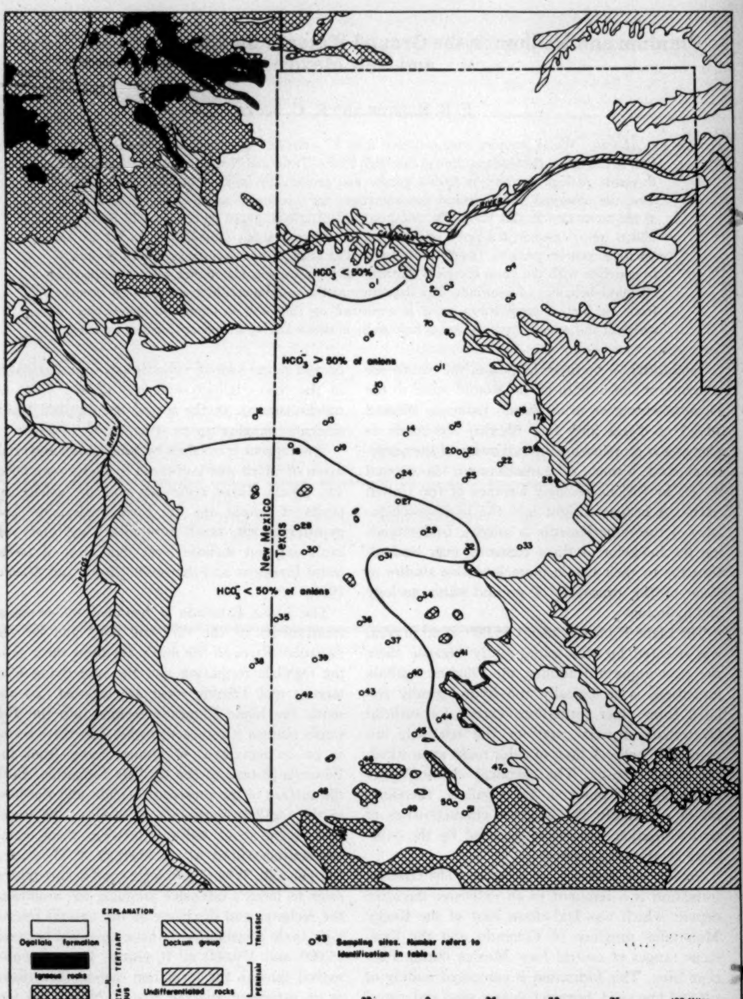
The Llano Estacado, about 35,000 sq mi in area, was selected for this initial study because there the most important aquifer, the Pliocene Ogallala formation, is geologically and hydrologically isolated from other formations except for surficial Quaternary deposits, and for the relatively impermeable bedrock floor of older rocks upon which the Ogallala rests. The chemical characteristics of the ground water in the Ogallala, therefore, reflect essentially the inherent characteristics of that formation, somewhat modified by the overlying Quaternary deposits.

Geology and hydrology of the area—The Ogallala formation is a remnant of an extensive fluviatile deposit which was laid down east of the Rocky Mountains province of Colorado and the limestone ranges of central New Mexico during Pliocene time. This formation is composed mainly of silt and fine sand; however, coarse sand and gravel are present throughout. The coarser facies occur principally in broad valleys in the sub-Ogallala floor. Zones of lime-cemented caliche are common throughout the formation, and at a few horizons discontinuous beds of volcanic ash are intercalated in the finer grained sediments [*Theis*, 1936]. A caliche caprock at the top of the Ogallala has a thickness ranging up to several tens of feet.

The caprock is overlain by wind-blown material, much of which was laid down in Pleistocene lakes and ponds. These sediments and the eolian deposits of Recent age are chiefly calcareous and gypsiferous silt, sand, bentonitic clay, and volcanic ash but include local thin beds of fresh-water limestone and diatomite [*Evans* and *Meade*, 1944].

The Llano Estacado is bounded by erosional escarpments on the east and west and by the Canadian River on the north. On these three sides the Ogallala formation and the underlying Cretaceous and Triassic rocks are exposed. To the south the Llano Estacado merges into the Edwards plateau (Cretaceous rocks), but there seems to be no movement of ground water from the Edwards plateau to the Ogallala formation. Both the surface of the present-day plain and the base of the Ogallala formation, as well as the water table lying about halfway between them, slope east-southeastward at an average of about ten feet per mile. When hydrologic equilibrium existed prior to today's intensive pumping for irrigation, the recharge and discharge in the natural hydrologic cycle is estimated to have averaged between 75,000 and 150,000 ac ft yearly. Ground water moved through the formation east-southeastward at an estimated average rate of 200 to 300 feet per year [*White*, *Broadhurst*, and *Lang*, 1946].

Most wells in the Ogallala formation yield water of relatively good quality. Recharge is derived entirely from precipitation on the surface of the


HCO$_3^-$ < 50%
HCO$_3^-$ > 50% of anions
HCO$_3^-$ < 50% of anions
New Mexico
Texas
CANADIAN RIVER
PECOS RIVER
1
2
3
4
5
6
7
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9
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48
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50
51
EXPLANATION
Ogallala formation
Igneous rocks
TERTIARY
Undifferentiated rocks
CRETACEOUS
Dockum group
TRIASSIC
Undifferentiated rocks
PERMIAN
o43 Sampling sites. Number refers to identification in table I.
25
0
25
50
75
100 Miles

FIG. 1 - Geologic map of the Llano Estacado, Texas and New Mexico [after *Barnes* and others, 1949] showing sampling sites and areas of differing chemical quality of the ground water

TABLE 1 – *Sampling sites and characteristics of ground water from the Llano Estacado*

No. on Fig. 1	Location	Source	Uranium conc.	Radium conc.	Bicarbonate conc.	Alkali metals percentage[a]	Dissolved solids	Remarks
			ppb	μμc/l	epm		ppm	
1	Vega, Texas	Well	5.0	0.1	4.03	35	564	
2	14 mi SW of Amarillo, Texas	Well	6.6	0.1	4.92	22	367	
3	Amarillo, Texas	Well	6.7	0.8	4.98	19	356	
4	Panhandle, Texas	Well	5.4	0.3	4.59	14	296	
5	Claude, Texas	Well	7.2	0.2	4.77	26	380	
6	3 mi N of Hereford, Texas	Well	3.5	0.2	5.42	28	404	
7	Canyon, Texas	Well	6.7	0.9	5.77[b]	87[c]	390[c]	Triassic sand
8	14 mi SE of Canyon, Texas	Well	3.1	0.2	4.34	28	322	
9	2 mi W of Friona, Texas	Well	4.2	0.2	4.03	34	306	
10	Dimmit, Texas	Well	5.8	0.1	4.70	23	714	
11	4.5 mi W of Happy, Texas	Well	5.0	0.1	5.05	28	306	
12	Clovis, New Mexico	Well	4.7	0.1	3.786	29	264	
13	12 mi NE of Muleshoe, Texas	Well	6.9	0.1	4.31	24	300	
14	3 mi SW of Hart, Texas	Well	6.0	0.2	5.26	21	367	
15	Kress, Texas	Well	5.8	0.3	5.56	27	380	
16	Silverton, Texas	Well	9.0	0.4	6.23	66	444	Triassic
17	8 mi NW of Quitague, Texas	Spring	7.8	0.1	5.90	32	446	
18	8½ mi NW of Muleshoe, Texas	Well	3.6	0.2	3.46	20	551	
19	8 mi NE of Muleshoe, Texas	Well	7.4	0.1	4.95	27	402	
20	10½ mi NW of Hale Center, Texas	Well	4.8	0.1	5.03	17	366	
21	Plainview, Texas	Well	6.6	0.1	5.47	28	406	
22	5 mi NW of Lockney, Texas	Well	8.3	0.2	5.77	28	410	
23	10 mi NE of Floydada, Texas	Spring	8.2	0.2	5.34	22	384	
24	2.1 mi N of Hart Camp, Texas	Well	3.9	0.1	4.85	17	384	
25	11 mi S of Plainview, Texas	Well	0.9	<0.1	5.57	26	406	Cretaceous limestone
26	10 mi NE of Dougherty, Texas	Spring	3.6	0.1	4.62	74	982	Cretaceous
27	4.9 mi SE of Littlefield, Texas	Well	10	0.3	4.90	30	812	
28	6.2 mi W of Morton, Texas	Well	5.5	0.1	3.77	46	1040	
29	1½ mi N of Shallowater, Texas	Well	11	0.1	4.88	34	1240	
30	7 mi SSW of Morton, Texas	Well	4.8	<0.1	4.23	25	616	
31	6 mi E of Levelland, Texas	Well	11	<0.1	5.62	31	593	
32	5 mi S of Idalou, Texas	Well	12	0.2	4.64	22	947	
33	4 mi E of Ralls, Texas	Well	7.4	0.2	5.92	41	405	
34	8 mi W of New Home, Texas	Well	12	<0.1	7.59	58	638	
35	1.6 mi E of Bronco, Texas	Well	3.1	0.2	3.21	39	598	
36	10 mi WNW of Brownfield, Texas	Well	3.1	<0.1	4.15	25	570	
37	10 mi S of Brownfield, Texas	Well	11	0.1	4.84	27	889	
38	Lovington, New Mexico	Well	1.2	0.1	3.28	27	434	
39	6 mi E of Denver City, Texas	Well	3.8	0.1	3.77	33	695	
40	6 mi NE of O'Donnel, Texas	Well	46	0.2	1.97	25	14,800	Prob. cretaceous and older
41	12 mi N of Lamesa, Texas	Well	8.2	0.1	5.02	29	840	
42	13.5 mi W of Seminole	Well	2.7	0.3	3.70	27	547	
43	19 mi ENE of Seminole, Texas	Well	19	1.4	4.59	51	1,070	Mixed[d]
44	13 mi ESE of Lamesa, Texas	Well	9.2	<0.1	5.83	47	528	
45	15.5 mi SW of Lamesa, Texas	Well	12	0.8	4.65	31	1,010	
46	6 mi E of Andrews, Texas	Well	3.4	0.1	4.18	42	734	
47	5 mi N of Big Spring, Texas	Well	4.1	0.8	4.75	14	516	
48	15 mi SW of Andrews, Texas	Well	1.9	0.1	3.18	35	749	
49	7.5 mi N of Midland, Texas	Well	7.6	<0.1	3.33	33	889	
50	Stanton, Texas	Well	6.3	<0.1	4.31	39	1,010	
51	12 mi S of Stanton, Texas	Well	28	0.1	4.29	42	686	Mixed[d]
52	Goldsmith, Texas	Well	5.9	0.3	3.28	33	644	

[a] Percentage of total cations, based on equivalents per million (epm).

[b] This sample also contained 0.07 epm carbonate ion.

[c] Percentage alkali metals and total dissolved solids concentration determined on composite sample from four municipal wells of city of Canyon. All of these wells are of similar depth and obtain water from Triassic rocks.

[d] These wells probably draw water from two or more formations.

plain. On the average, only a small fraction of an inch of the annual rainfall reaches the ground-water body. It is believed that there is little, if any, upward leakage of the highly mineralized water in the underlying Cretaceous and Triassic rocks into the Ogallala formation.

Scope of sampling network—Figure 1 shows the locations of the sampling sites. Samples of water from 47 wells and springs in the Ogallala formation of the Llano Estacado were collected and analyzed. Four samples of water from the older formations and three samples from wells supplied by two or more formations also were collected and analyzed for comparison. A description of the source, radium and uranium concentrations, and other pertinent data for each sample are given in Table 1. Uranium concentrations are in parts per billion, radium concentrations are in micromicrocuries per liter and bicarbonate concentrations are in equivalents per million.

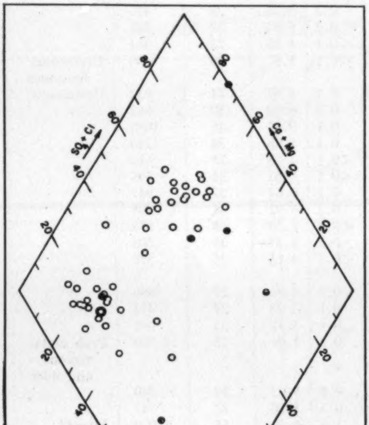

FIG. 2 – Classification of ground water from the Llano Estacado according to its chemical character

Chemical character of the samples—The samples of ground water from the Ogallala may be divided into two groups having slightly different chemical characters. Those from the northeastern part of the Llano Estacado have a much higher percentage concentration of bicarbonate ion, based on equivalents per million, than those from the southwestern part.

The differences in the chemical character of the two groups are illustrated in Figure 2. The chemical character of each sample is shown by the percentages of the major chemical constituents in the total ionic content.

Probably most of the recharge from precipitation reached the Ogallala via the overlying Quaternary deposits, and differences in the chemical character of the two groups reflect differences in the composition of the Quaternary deposits in different areas on the plain. The high-bicarbonate water represents chemical leaching of the lacustrine material in which silt, sand, and volcanic ash predominate. The area from which the samples of water high in sulfate and chloride were collected is adjacent to the Pecos River basin in New Mexico. Large exposures of gypsiferous materials and other evaporites are found in this river basin and other areas in southern New Mexico. The prevailing winds from the west remove gypsiferous and saliferous dust from southern New Mexico and deposit it in depressions on the southern part of the Llano, after which sulfate and chloride salts are carried into the underlying formations and to the ground-water reservoir by percolating meteoric water.

Uranium content of the waters—All samples were analyzed for uranium content by the fluorimetric method [*Thatcher* and *Barker*, 1957]. The concentrations of uranium in water from the Ogallala formation ranged from 0.9 to 12 parts per billion (ppb) with a median of 6.2 ppb. These concentrations are relatively high compared to the uranium content of 67 random samples from fluviatile sedimentary aquifers throughout the United States. The uranium concentration in these random samples ranged from <0.1 to 22 ppb with a median of 1.6 ppb.

The areal distribution of the uranium concentrations in the samples from the Ogallala are shown by an isogram map, Figure 3. A trend of increasing uranium content in the water seems to coincide with the general direction of ground-water movement.

The downgradient increase in uranium content probably is a result of the water at successive downgradient locations having been in the aquifer longer than water obtained from upgradient sources. Local variations in chemical character and content of radioelements probably reflect the effects of the increments of recharge from nearby playas and other depressions whose bottoms are permeable enough to permit recharge to the Ogallala. Such areas commonly contain highly mineralized zones of evaporites, probably including some uranium salts. These materials may be dissolved by the percolating waters and thereby create local anomalies in the chemical character of the ground water. The two sources from the Ogallala formation having the highest uranium content, 43 and 51 in Table 1, are somewhat anomalous and possibly represent notable examples of such a situation.

The uranium concentrations tend to correlate with the total dissolved solids in the waters, as is shown in Figure 4. Again, two distinct groups of plotted points are observed which correspond to the groups of high and low bicarbonate percentage composition shown in Figure 2. The correlation index for the high-bicarbonate group is 0.7 and that for the low-bicarbonate group is 0.6, which indicate definite trends. These trends are consistent with the theoretical considerations of the solution of soluble substances.

Another tendency toward correlation is shown by a plot of uranium concentration against bicarbonate concentration, Figure 5. The coefficient of correlation between these variables is 0.6. This relationship probably is the result of the formation of the very stable, soluble, anionic, uranyl-carbonate complexes which are formed according to the following equations

$$HCO_3^- \rightleftharpoons H^+ + CO_3^= \tag{1}$$

$$UO_2^{++} + 2CO_3^= + 2H_2O \rightleftharpoons UO_2(CO_3)_2(H_2O)_2^= \tag{2}$$

$$UO_2^{++} + 3CO_3^= \rightleftharpoons UO_2(CO_3)_3^{-4} \tag{3}$$

Applying the law of mass action to these equations shows that an increase in the concentration of bicarbonate ions tends to decrease the concentration of the uranyl ions through the formation of the uranyl-carbonate complexes. A decrease in concentration of uranyl ions enhances any mechanism by which uranyl ions come into solution. The formation of aqueous uranyl ions is probably one step in most processes whereby uranium is dissolved from pre-existing uranyl compounds or other uranium species existing in the solid phase in the formation. Therefore, the solvent power of the water for uranium is increased with increasing bicarbonate content.

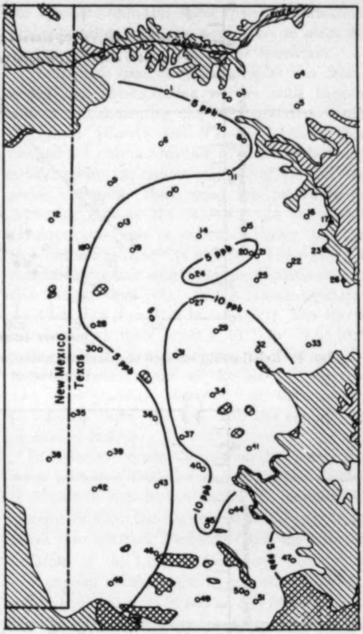

FIG. 3 – Isogram lines of uranium concentration in the ground water of the Llano Estacado (see Fig. 1)

Radium content of the waters—In the course of its radioactive decay, uranium gives rise to a series of other radioactive nuclides, including radium^{226}, as follows: $U^{238} \xrightarrow{(4.51 \times 10^9 y)} Th^{234} \xrightarrow{(24.1d)} Pa^{234} \xrightarrow{(1.14m)} U^{234} \xrightarrow{(2.67 \times 10^5 y)} Th^{230} \xrightarrow{(8.0 \times 10^4 y)} Ra^{226} \xrightarrow{(1620y)}$ other daughter nuclides. The times indicated are the half-lives of the nuclides undergoing each transformation [*Kirby*, 1953, p. 17]. The amount of any member of such a series present in a closed system containing one or more of its precursors may be calculated by a method devised by *Bateman* [1910]. For radium^{226} and for any time greater than ten years, this method gives rise to the expression

$$Ra_t^{226} = (3.41 \times 10^{-7} \exp[-1.54 \times 10^{-10} t] - 4.9 \times 10^{-7} \exp[-2.6 \times 10^{-6} t] + 1.5 \times 10^{-7} \exp[-8.7 \times 10^{-6} t]) U_0^{238} + (8.4 \times 10^{-3} \exp[-2.6 \times 10^{-6} t] - 8.5 \times 10^{-3}$$

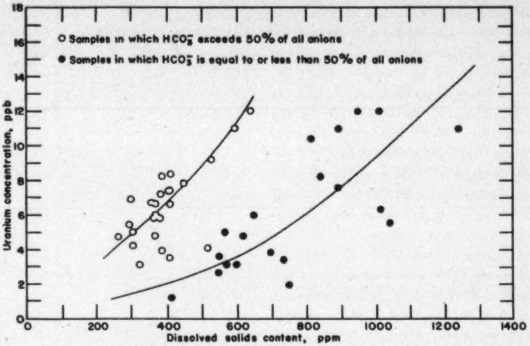

FIG. 4 – Relationship between uranium concentration and dissolved solids content of water from the Ogallala formation of the Llano Estacado

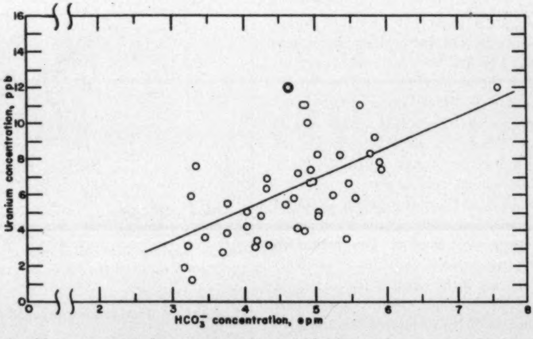

FIG. 5 – Relationship between uranium concentration and bicarbonate ion concentration in water from the Ogallala formation of the Llano Estacado

$$\exp[-8.7 \times 10^{-6}t] + 1.23 \times 10^{-4} \exp[-4.28 \times 10^{-4}t]) (Th_0^{234} + Pa_0^{234} + U_0^{234}) + 2.0 \times 10^{-2} (\exp[-8.7 \times 10^{-6}t] - \exp[-4.28 \times 10^{-4}t]) Th_0^{230} + \exp[-4.28 \times 10^{-4}t] Ra_0^{226}$$

where Ra_t^{226} = weight of radium^{226} at time t
U_0^{238}, Th_0^{234}, etc = weight of uranium^{238}, thorium^{234}, etc. at time zero
t = elapsed time from any arbitrary zero

As the time becomes very large, the above equation reduces to

$$Ra_t^{226} = 3.41 \times 10^{-7} U_0^{238} \exp[-1.54 \times 10^{-10}t] = 3.41 \times 10^{-7} U_t^{238}$$

indicating that equilibrium is established between the radium and the uranium. The time required for this equilibrium to be attained depends upon the initial concentrations of the various nuclides intermediate between uranium and radium. If significant quantities of any of the substances involved are added or removed from the system, radioactive equilibrium would not be established, although another equilibrium involving the rate of addition or removal might be possible.

In any geologic terrane which has been completely isolated, so far as transfer of material is concerned, for one million years (assumed time from beginning of the Pleistocene to the present), the Bateman solution for radium^{226} is

$$Ra^{226} = 3.05 \times 10^{-7} U_0^{238} + 6.20 \times 10^{-4} (Th_0^{234} + Pa_0^{234} + U_0^{234}) + 3.42 \times 10^{-6} Th_0^{230}$$

Uranium^{238} and uranium^{234} are chemically identical; therefore, they would be deposited in approximately the same ratio as they occur naturally, or

$$U_0^{234}/U_0^{238} = 5.7 \times 10^{-5}$$

Thorium^{234} and protactinium^{234} occur in such small quantities compared to uranium^{238} that even if there were a million-fold enrichment during deposition, the effect upon the radium content would be negligible. It is difficult to achieve an enrichment of this magnitude in one step even in the laboratory using the most favorable methods; therefore, it is probably not often achieved in nature, and these intermediate nuclides may be neglected. An approximate expression is then

$$Ra^{226} \approx 3.4 \times 10^{-7}\ U_0^{238} + 3.4 \times 10^{-6}\ Th_0^{238}$$

or

$$Ra^{226} \approx (3.4 \times 10^{-7} + 6.1 \times 10^{-11}k)\ U_0^{238}$$

where

$$k = Th^{230} \text{ enrichment factor} = \frac{\text{ratio of } Th^{230} \text{ to } U^{238} \text{ deposited}}{\text{radioactive equilibrium ratio of } Th^{230} \text{ to } U^{238}}$$

Thus, regardless of initial conditions, the radium^{226} must be present approximately in equilibrium with the uranium or in excess as determined by the thorium^{230} enrichment during deposition.

The ratio of radium^{226} to uranium in waters from a formation may indicate something of the history of or conditions in the formation, but the two elements differ widely in chemical behavior and the amounts found in water from the formation probably never have the same ratio as amounts existing in the solid state in the formation.

The radium content of the samples was determined by coprecipitating radium with barium sulfate and measuring the alpha-activity of the precipitate [*Barker* and *Thatcher*, 1957]. This method not only is sensitive to radium^{226} but also is affected by the radium member of the thorium series, radium^{224}. Thus, using this procedure to determine radium, the values of the radium-to-uranium ratios may be somewhat higher than the true ratio of radium^{226} to uranium. The measured radium contents in water from the Ogallala formation ranged from <0.1 to 0.8 micromicrocuries per liter with a median of 0.1 $\mu\mu c/l$. The Ra/U ratios ranged from $<0.8 \times 10^{-8}$ to 19×10^{-8} microcuries Ra per microgram U. The radioactive equilibrium value of the Ra^{226}/U ratio is 34.1×10^{-8} $\mu c/\mu g$; therefore, all the samples of Ogallala water had less than the equilibrium amount of radium.

In order to explain the radium deficiency, one must postulate that the radium in the aquifer is present in less than its radioactive equilibrium amount or that the uranium is being selectively taken into solution. Because of the age and the isolation of the Ogallala formation, equilibrium or a radium excess should have been established, unless large amounts of ionium had been removed during Pleistocene time or large amounts of radium had been removed during Recent time. The only mechanism for this removal would be

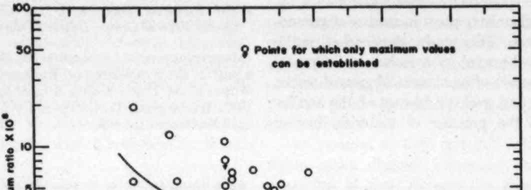

FIG. 6 – Relationship between the radium-uranium ratio and percentage of alkali metal ions in water from the Ogallala formation of the Llano Estacado

by ground-water discharge along the eastern escarpment. Such loss of radium is very minor today and probably was relatively minor during both Recent and Pleistocene times. In addition, the chemistry of ionium is such that it is not likely that large amounts would be removed by ground water from the formation.

A more reasonable explanation for the radium deficiency in the ground water might be ion exchange. If the radioelements in the formation occur in a certain ratio, the uranium and radium should be available for solution in that same ratio. However, as soon as they entered the solution phase, much of the uranium would be complexed by the carbonate ions present and would appear in an anionic form. These anionic complexes would not be subject to adsorption by cation-exchange mechanisms, whereas the uncomplexed radium cations could be adsorbed by clays and other minerals having cation-exchange capacity. The ground water would then contain an excess of uranium over radium, as was observed.

Some supporting evidence for this hypothesis is obtained from a plot of the radium-uranium ratio against the percentage of alkali metals (based on equivalents per million) present in solution as shown in Figure 6. The correlation index of 0.45 suggests a possible relationship between the two variables. If an increase in alkali metal ion percentage is taken as an indication of the occurrence of ion-exchange, the decrease of the radium-uranium ratio may be logically suggested to be a result of the same process.

Conclusion—Radioelement determinations used with ordinary chemical analyses will enhance the part that geochemistry plays in studies of groundwater resources. This study shows that radioelements may be used to corroborate inferences as to the direction of movement of ground water, the lithology and geologic history of the aquifer material, and the presence of materials having ion-exchange capacity. It is apparent that tentative geochemical conclusions reached in this investigation may be refined by further work; specifically recommended is sampling of formational water at known horizons in the Pleistocene lacustrine deposits and determinations of radium in clay samples from both the Ogallala and the Pleistocene sediments.

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Disposal of Radioactive Waste on Land

H. H. HESS AND W. R. THURSTON

Abstract—Two years' consideration of the disposal problem by the National Research Council Committee on Waste Disposal has led to certain conclusions which are presented. Waste may be safely disposed of at many sites in the United States but conversely there are many large areas in which it is unlikely that disposal sites can be found as, for example, the Atlantic seaboard. The research to ascertain feasibility of disposal has for the most part not yet been done. The most practical immediate solution of the problem suggests disposal in cavities mined in salt beds or domes. Disposal could be greatly simplified if the waste could be gotten into solid form of relatively insoluble character. Disposal in porous beds underground has capabilities of taking large volumes but will require considerable research to make the waste compatible with such an environment. The main difficulty with this method at present is to prevent clogging of pore space as waste is pumped in.

Summary—A committee of geologists and geophysicists was established by the National Academy of Sciences-National Research Council at the request of the Atomic Energy Commission to consider the possibilities of disposing of radioactive wastes within the continental limits of the United States. The group was charged with assembling the existing geologic information pertinent to disposal, delineating the unanswered problems associated with the disposal schemes proposed, and point out areas of research and development meriting first attention; the committee is to serve as continuing adviser on the geological and geophysical aspects of disposal and the research and development program.

The Committee with the cooperation of the Johns Hopkins University organized a conference at Princeton in September 1955. After the Princeton Conference members of the committee inspected disposal installations and made individual studies. Two years' consideration of the disposal problems leads to certain general conclusions. The research to ascertain feasibility of disposal has for the most part not yet been done. A preliminary report has been published [*Committee on Waste Disposal*, 1957].

Wastes may be disposed of safely at many sites in the United States but, conversely, there are many large areas in which it is unlikely that disposal sites can be found, for example, the Atlantic Seaboard.

Storage in tanks is at present the safest and possibly the most economical method of containing waste.

Disposal in salt is a very promising method for the near future. Research should be pushed immediately on the structural problem of stability with respect to size of cavities at a given depth; on the thermal problem (getting rid of the heat or keeping it down to acceptable levels); and on the economics of such disposal.

Also very promising is the stabilization of the waste in a slag or ceramic material forming a relatively insoluble product. This could be placed in dry mines, surface sheds, or large cavities in salt.

In the future the injection of large volumes of dilute liquid waste into porous rock strata at depths in excess of 5,000 feet may become feasible but means of rendering the waste solutions compatible with the mineral and fluid components must first be developed. The pumping of wastes into porous beds interstratified with impermeable formations in a synclinal structure is an interesting possibility for disposing of the large volumes of wastes to be expected in the future. The composition of the rocks and the connate waters are both variable as will be the composition of the waste solutions so an almost infinite variety of circumstances result. The problem would have to be solved first for a given bed at a given site for a given waste solution at a given dilution.

The removal of Cs^{137} and Sr^{90} from the waste would make disposal somewhat easier for the waste free of these isotopes but does not change qualitatively the recommendations made in the report.

Continuing disposal even of low level waste in the vadose water zone is of limited application and probably involves unacceptable long-term risks.

In the complex relation between (a) storage time of waste for cooling, (b) transportation cost in shielded carriers, and (c) distance to disposal site, the last of these factors must be considered before locating any plant which produces large quantities

of waste, remembering that there are large sectors of the country where disposal is not possible.

The movement of gross quantities of fluids through porous media is reasonably well understood by hydrologists and geologists, but whether this is accomplished by forward movement of the whole fluid mass at low velocity or whether the transfer is accomplished by rapid flow in "ribbons," is not known. In deep disposal of waste in porous media it will in many cases be essential to know which of these conditions exists. This will be a difficult problem to solve.

The education of a considerable number of geologists and hydrologists in the characteristics of radioactive wastes and its disposal problems is going to be necessary.

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Fitting a Generalized Log-Normal Distribution to Hydrologic Data

D. L. BRAKENSIEK

Abstract—A statistical distribution is developed which makes it possible to fit a wide range of positively skewed hydrologic data. It is shown that the general least-squares fitting equations will reduce to simple forms for fitting a normal, log-normal or extreme-value distribution to data. Two fitting processes are developed for fitting data by the so-called generalized log-normal distributions. Examples are given for illustrating the fitting procedures.

Introduction—Three statistical distributions currently find wide use in hydrologic frequency analyses, that is, the normal, log-normal, and extreme-value distributions. It is the purpose of this paper to develop a generalized log-normal statistical distribution. This general frequency distribution would tend to unify the frequency-analysis problem for the hydrologist and at the same time give him a more versatile tool.

Basic in the development of a generalized log-normal distribution was the idea of a modified log-normal distribution which was mentioned by *Hazen* [1930]. Also, a recent investigation by *Chow* [1954] on the skew factors of a log-normal distribution was important in its development. Following the formulation of the frequency distribution, least-squares fitting equations are presented. Included as special cases are simple least squares fitting equations for the normal, extreme-value, and log-normal distributions. A slightly more laborious least-squares fitting procedure is presented for other positively skewed distributions.

Examples utilizing the least squares fitting equations are given. Examples include one each for the normal, log-normal, and extreme-value distributions, and one considers the case in which no specific distribution is assumed. While the latter case reduces to a pure curve fitting exercise it may be justified in certain cases as an expediency.

Symbols—The following symbols are used.

x	observed variate
U	transformed variate
$\bar{x}$, $\bar{U}$	mean of the set of each variate
K	frequency factor
C_v	coefficient of variation of the set of x variates
CV	coefficient of variation of the set of U variates
z	standardized normal deviate
n	number of observed variates
m	order number of each variate when they are first ranked in decreasing order.

Formulation of distribution—As pointed out by *Chow* [1951] a hydrologic variable, for example, annual peak runoff rates, may be related to its parent frequency distribution by the equation

$$x/\bar{x} = 1 + C_v K \qquad \text{(1a)}$$

or

$$x = \bar{x} + \bar{x} C_v K \qquad \text{(1b)}$$

Making the assumption that the x variable may be transformed to a log-normal variate leads to a new frequency equation for the transformed variate U

$$U/\bar{U} = 1 + CV\,K \qquad \text{(2)}$$

Eq. (2) is related to (1a) by the linear transformation

$$U/\bar{U} = k(x/\bar{x}) + (1 - k) \qquad \text{(3)}$$

where $k = (CV/C_v)$. From *Chow's* [1954] investigation the right-hand side of (2), since U by hypothesis is a log-normal variate, can be written

$$1 + CV\,K = \exp\,[bz - (b^2/2)] \qquad \text{(4)}$$

where

$$b = \sqrt{\ln\,(1 + CV^2)}$$

and z is the standardized normal deviate. Combining (2) and (4) leads to the frequency distribution of U, a generalized log-normal variate

$$U/\bar{U} = \exp\,[bz - (b^2/2)] \qquad \text{(5)}$$

in which z is the independent variable.

In the usual manner, least squares fitting equations for the U-distribution are found to be

$$\hat{k} = \exp\,(-b^2/2)\;[\Sigma(x/\bar{x} - 1)\exp\,(bz)/\Sigma(x/\bar{x} - 1)^2] \qquad \text{(6a)}$$

and

$$\hat{b}^2 + 2\hat{b}/n[\Sigma z^2 + \Sigma\,\ln\,(U/\bar{U})] = 2/n\,\Sigma z\ln U \qquad \text{(6b)}$$

To be of practical use the solutions of (6a) and (6b) or both must be obtained by routine computational procedures. The following section will consider this requirement in some detail.

Computational procedures—The normal and extreme value distributions are simply fitted to data by using an adaptation of (6a). This adaptation requires the first two terms of the expansion of $\exp\,(bz) = 1 + bz + \cdots$ and the identity $b = CV$. These approximations are sufficiently accurate for values of CV up to $CV = 0.45$. Recalling the definition of k, (CV/C_v), and substituting the above approximations into equation (6a) one obtains

$$\bar{x}C_v = \exp(CV^2/2) \sum(x - \bar{x})^2/\sum xz \quad \text{(7a)}$$

For a normal distribution one has $CV = 0$. Hence a least-squares fit of that distribution to data would follow from the equation

$$\bar{x}C_v = \sum(x - \bar{x})^2/\sum xz \quad \text{(7b)}$$

where the values of z are read from a table of areas of the normal distribution.

For an extreme value distribution *Chow* [1954] has shown that $CV = 0.364$. Hence the least squares fitting equation would be

$$\bar{x}C_v = 1.067\ (\sum(x - \bar{x})^2/\sum xz) \quad \text{(7c)}$$

A log-normal distribution postulates that $k = (CV/C_v) = 1$. Hence (6b), for the least squares fit of a log-normal distribution to data, becomes a cubic equation in $\hat{b}$

$$\hat{b}^3 + 2\hat{b}/n(\sum z^2 + \sum \ln(x/\bar{x})] = 2/n\sum z \ln(x/\bar{x}) \quad \text{(8a)}$$

A satisfactory first approximation for $\hat{b}$ in (8a) follows from

$$b = \sum z \ln x/\sum z^2 \quad \text{(8b)}$$

If the value of b is small, say less than 0.5, then the estimate obtained from (8b) would be satisfactory. The definition $b = \sqrt{\ln(1 + CV^2)}$ allows the calculation of C_v as for this case $C_v = CV$.

For the above three distributions the actual data fitting equation is based on (1b), that is, $x = \bar{x} + \bar{x}\,C_vK$. The value of $\bar{x}$, the mean, is calculated in the usual manner and the value of $\bar{x}C_v$ follows from (7b), (7c), or (8a). Further, the values of K, found in Table 1, correspond to $CV = 0$, $CV = 0.364$ and $CV = C_v$ for the normal, extreme-value, and log-normal distributions respectively. If for each distribution the data is plotted on its respective probability paper, the two arbitrary calculated points, (x_1, K_1) and (x_2, K_2), would fix the least squares line of fit.

In general, for any case that the positive skew, as defined by the identity $CS = 3\ CV + CV^3$, [*Chow*, 1954] can be postulated, (6a) would be computationally feasible. Values of the exponential term, $\exp(bz)$, are tabled in most mathematical handbooks. For cases in which nothing is known of the skew of the parent population, (6a) and (6b) must be solved by other methods. The first method described below would be satisfactory for values of CV less than 0.45. However, even for larger values a workable fit to data would be obtained. The value of this procedure stems from being a quick, visual procedure.

Substituting the value of $\bar{x}C_v$ from (7a) into (1a) one has

$$x = \bar{x} + B \exp(CV^2/2)K \quad \text{(9)}$$

where $B = \sum(x - \bar{x})^2/\sum xz$. Eq. (9) may be used in a simple procedure for obtaining a visual estimate of CV. The procedure would be as follows: (1) Plot the x-data on log-normal probability paper

TABLE 1 – *Theoretical log-probability frequency factors*[a]

CV	K values for probability in percentage equal to or greater than the given variate								
	99	95	80	50	20	5	1	0.1	0.01
	−	−	−	−	+	+	+	+	+
0.000	2.33	1.65	0.84	0.00	0.84	1.64	2.33	3.09	3.72
0.010	2.31	1.64	0.85	0.01	0.84	1.65	2.35	3.13	3.79
0.020	2.29	1.63	0.85	0.02	0.84	1.66	2.38	3.17	3.85
0.030	2.27	1.63	0.85	0.02	0.84	1.67	2.40	3.22	3.91
0.040	2.24	1.62	0.85	0.03	0.84	1.68	2.42	3.26	3.98
0.050	2.22	1.61	0.85	0.03	0.83	1.69	2.44	3.30	4.05
0.060	2.20	1.60	0.85	0.04	0.83	1.69	2.46	3.35	4.12
0.070	2.18	1.59	0.85	0.04	0.83	1.70	2.49	3.40	4.19
0.080	2.16	1.58	0.85	0.05	0.82	1.71	2.51	3.45	4.26
0.090	2.13	1.57	0.85	0.05	0.82	1.72	2.53	3.50	4.34
0.100	2.11	1.56	0.85	0.06	0.82	1.72	2.55	3.56	4.42
0.125	2.06	1.54	0.85	0.07	0.81	1.74	2.61	3.67	4.61
0.150	2.01	1.51	0.86	0.08	0.81	1.76	2.66	3.80	4.81
0.175	1.96	1.49	0.85	0.09	0.80	1.78	2.72	3.92	5.03
0.200	1.91	1.46	0.85	0.10	0.79	1.79	2.78	4.05	5.24
0.225	1.86	1.44	0.85	0.11	0.78	1.81	2.83	4.18	5.48
0.250	1.81	1.41	0.84	0.12	0.77	1.82	2.88	4.32	5.71
0.275	1.77	1.39	0.84	0.13	0.76	1.83	2.94	4.46	5.96
0.300	1.72	1.36	0.84	0.14	0.75	1.84	2.99	4.60	6.19
0.325	1.68	1.34	0.83	0.15	0.74	1.85	3.04	4.74	6.44
0.350	1.63	1.32	0.83	0.16	0.73	1.86	3.10	4.88	6.70
0.375	1.59	1.29	0.82	0.17	0.72	1.87	3.15	5.02	6.96
0.400	1.55	1.27	0.82	0.18	0.71	1.87	3.20	5.16	7.22
0.425	1.51	1.24	0.81	0.19	0.70	1.88	3.25	5.30	7.49
0.450	1.47	1.22	0.81	0.20	0.69	1.88	3.30	5.44	7.78
0.475	1.43	1.20	0.80	0.20	0.68	1.89	3.34	5.58	8.06
0.500	1.40	1.17	0.80	0.21	0.66	1.89	3.38	5.71	8.35
0.525	1.37	1.15	0.79	0.22	0.65	1.89	3.42	5.86	8.65
0.550	1.34	1.13	0.78	0.22	0.64	1.89	3.46	6.00	8.96
0.575	1.31	1.11	0.78	0.23	0.63	1.89	3.50	6.14	9.27
0.600	1.28	1.09	0.77	0.24	0.61	1.89	3.53	6.27	9.57
0.625	1.24	1.07	0.76	0.24	0.60	1.89	3.57	6.41	9.88
0.650	1.22	1.05	0.76	0.25	0.59	1.89	3.60	6.55	10.20
0.675	1.19	1.03	0.75	0.26	0.58	1.89	3.63	6.70	10.51
0.700	1.16	1.01	0.74	0.26	0.57	1.88	3.66	6.83	10.83
0.725	1.13	0.99	0.73	0.27	0.56	1.88	3.69	6.97	11.15
0.750	1.11	0.98	0.73	0.27	0.54	1.87	3.71	7.10	11.48
0.775	1.08	0.96	0.72	0.27	0.53	1.87	3.74	7.24	11.80
0.800	1.06	0.94	0.71	0.28	0.52	1.86	3.76	7.37	12.12
0.825	1.03	0.92	0.70	0.28	0.51	1.85	3.78	7.50	12.45
0.850	1.01	0.91	0.70	0.28	0.50	1.85	3.80	7.62	12.79
0.875	0.99	0.89	0.69	0.29	0.48	1.84	3.82	7.74	13.11
0.900	0.97	0.88	0.68	0.29	0.47	1.83	3.84	7.86	13.44
0.925	0.95	0.86	0.67	0.29	0.46	1.82	3.86	7.98	13.77
0.950	0.93	0.85	0.67	0.29	0.45	1.81	3.88	8.09	14.08
0.975	0.92	0.83	0.66	0.29	0.43	1.79	3.90	8.20	14.39
1.000	0.90	0.82	0.65	0.29	0.42	1.78	3.91	8.30	14.70

[a] Adapted from *Chow* [1954]. Each column of Chow's Table 2 was plotted against CV. Values in this table were then read from these graphs.

using the plotting position formula $m/(n + 1)$. (2) Refer to Table 1, in which values of the frequency factor K for several probability values and for a range of CV's are given. Substitute values of K and the respective CV value into (9) and compute values of x. Then plot these values on the graph of (1) at their respective probability values, which are given at the top of each column. (3) The best visual fit of the calculated points to the observed points would define an estimate of CV.

The following procedure may be used for improving on the value of CV estimated visually or as an independent fitting process. This procedure is not limited by the magnitude of CV. The process would be most conveniently carried out in a tabular form such as is described below. (1) The first three columns of a tabular form would consist of ranked values, in decreasing order, of the observed variable, each plotting position, $m/(n + 1)$, and the corresponding value of the standardized normal deviate z, respectively. (2) Corresponding to the initial estimate of CV, CV_0, column 4 would be filled in with the K-values for each value of the ranked variate. These values would be obtained by the following scheme. From Table 1, pick two values of K from the corresponding CV_0 row, for example, the values of K for probability of 0.01 and 0.95. Corresponding to these two values of K pick off the corresponding two values of z, that is, from the first row of Table 1. On a sheet of semi-log paper plot the two values of $(K + 1/CV_0)$ as ordinate and the respective values of z as abscissa. By the nature of the definition of K [*Chow*, 1954], these two plotted points will uniquely fix a straight line. Now from this graph K-values may be read off for each ranked observation by referring to its z-value. (3) Calculate the simple correlation coefficient r of x on K. For a simpler calculation, one would calculate r^2, that is, $r^2 = [\Sigma(Q - \bar{Q})(K - \bar{K})]^2/\Sigma(Q - \bar{Q})^2 \Sigma(K - \bar{K})^2$. (4) For several other values of CV, above and below the first CV value, perform steps (2) to (3). In this way the value of CV which gives rise to the largest r^2 value can be approximately determined. It will generally happen that over a range of CV values the value of r^2 does not change appreciably. Hence, an approximate 'closest' fitting frequency equation can be obtained without actually 'pin-pointing' the optimum CV-value.

As pointed out, the above procedure is valid for any CV value. In those cases that a frequency analysis is simply a curve fitting problem it would probably have considerable merit. To facilitate bringing together the pertinent formulas for a particular frequency distribution, the following section will spell out procedures for fitting the three common distributions and also for the generalized log-normal distribution.

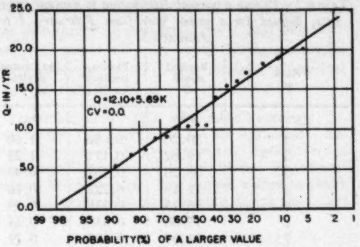

FIG. 1 – Normal distribution fitted to annual runoff

Empirical check of fitting procedures—All of the data utilized in the following cases were collected at the Soil and Water Conservation Research Station, Coshocton, Ohio.

The data used for checking the validity of (7b) for fitting a normal distribution represents annual runoff from Watershed 92. Following are the necessary computations.

By Eq. (7a), $\bar{Q}C_v = \Sigma(Q - \bar{Q})^2/\Sigma Qz = 5.69$.

By definition, $CV = 0$.

The fitted frequency equation, from Eq. (1b) is $Q = 12.10 + 5.69\,K$.

Calculating two points on the fitted line (Fig. 1): (a) Prob. = 0.05, $K = 1.64$; (b) Prob. = 0.95, $K = -1.65$

Substituting the K values into the frequency equation one finds that $Q = 21.4$ plots at 0.05 and $Q = 2.71$ at 0.95.

Table 2 shows computed values and Figure 1 shows the fitted normal distribution and the plotted data.

An extreme-value distribution was fitted to 24 hour maximum precipitation amounts. The calculations involved in solving (7c) are:

By Eq. (7c), $\bar{P}C_v = 1.067\,\Sigma(P - \bar{P})^2/\Sigma Pz = 0.76$.

By definition, $CV = 0.364$.

The fitted frequency equation, from Eq. (1b) is $P = 2.39 + 0.76\,K$.

Calculating two points on the fitted line (Fig. 2): (a) Prob. = 0.05, $K = 1.87$; (b) Prob. = 0.95, $K = -1.30$

Substituting the K value into the frequency equation one finds that $P = 3.81$ plots at 0.05

TABLE 2 – *Fitting a normal distribution to annual runoff data, defined for a water year from February 1 to January 31*

Rank m	Ranked runoff Q	Plotting position $m/(n+1)$	Std. normal deviate z
	in/yr		
1	20.20	0.056	1.60
2	19.02	0.111	1.22
3	18.20	0.167	0.97
4	17.19	0.222	0.76
5	16.25	0.278	0.59
6	15.66	0.333	0.43
7	14.09	0.389	0.29
8	10.65	0.444	0.14
9	10.63	0.500	0.00
10	10.58	0.556	−0.14
11	10.56	0.611	−0.29
12	9.22	0.667	−0.43
13	9.16	0.722	−0.59
14	7.54	0.778	−0.76
15	7.00	0.833	−0.97
16	5.52	0.889	−1.22
17	4.28	0.944	−1.60
Sum...............	205.75		
$\bar{Q}$...............	12.1029		

and $P = 1.40$ plots of 0.95. Figure 2 exhibits the data and the fitted distribution. Also included on this graph is the line of fit obtained by the fitting method proposed by *Gumbel* [1954].

A log-normal distribution was fitted to data comprising the runoff during the three month period, April–June, observed on Watershed 92. The computations are: $\sum z \ln Q = 7.471$.

By Eq. (8a), $b = 0.5082$, $CV = 0.543 = C_v$.

By Eq. (8b), $b = 0.5268$, $CV = 0.560$

The fitted frequency equation from Eq. (1b) is $Q = 4.25 + 2.31\,K$.

Calculating two points on the fitted line (Fig. 3): (a) Prob. = 0.05, $K = 1.84$; (b) Prob. = 0.95, $K = -1.14$.

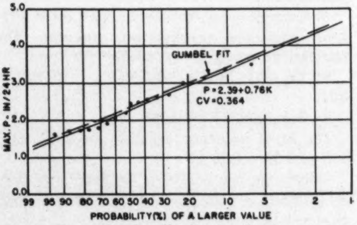

FIG. 2 – Extreme-value distribution fitted to 24-hour maximum precipitation

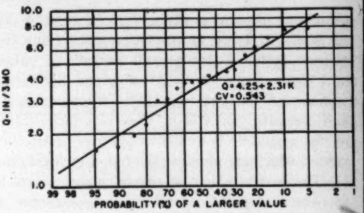

FIG. 3 – Log-normal distribution fitted to April–June runoff

Substituting the K value into the fitted frequency equation one finds that $Q = 8.62$ plots at 0.05 and $Q = 1.62$ plots at 0.95. The fitted distribution is given in Figure 3. It should be noted that (8a) and (8b), for this case, give nearly identical results.

Data to which a generalized log-normal distribution was fitted were annual maximum two-hour runoff amounts. No assumption was made on the amount of skew to assume. However, in actual practice an extreme value distribution might have been assumed. The computations are:

By Eq. (7a), $\bar{x}C_v = 0.1183 \exp(CV^2/2)$.

Visual fitting by Eq. (9), $Q = 0.22 + 0.12 \exp(CV^2/2)K$.

Calculated r^2 values: $r^2(CV = 0.0) = 0.967$; $r^2(CV = 0.1) = 0.973$; $r^2(CV = 0.2) = 0.972$; $r^2(CV = 0.4) = 0.958$.

The fitted frequency equation from Eq. (1b) is $Q = 0.22 + 0.12\,K$.

Points on the fitted curve (Fig. 4) are found in the same manner as in other examples except that more than two values of Q must be calculated in order to fix the curve.

The first step was determining a visual estimate

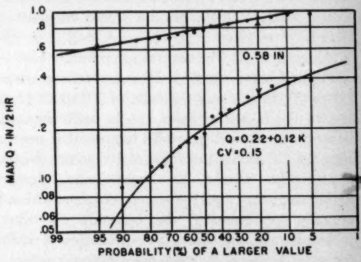

FIG. 4 – Generalized log-normal distribution fitted to two-hour maximum runoff

of CV. This value was determined to be 0.1. The final fit corresponds to a value of $CV = 0.15$. The r^2 value for $CV = 0.15$ was slightly more than the r^2 value for the extreme value CV value. Thus the more logical approach of utilizing a specific distribution would have given essentially the same fit.

Discussion—The numerous developments in frequency-analysis procedures in recent years has made it difficult for the analyst to keep abreast of new methodology. In this respect the generalized log-normal distribution would seem to be of value in that the analyst would not be required to have at hand a number of unrelated fitting procedures. The simple fitting procedure developed for the extreme value distribution would seem to compare quite well with an established fitting procedure and would seem to be simpler to apply.

A point of possible interest is the idea of transforming data so as to be made amenable by a certain distributional theory. For every set of data the determination of the parameter $k = CV/C_v$ fixes a transformation of the observed variates to more nearly log-normal variates. This transformation is given by

$$U = \bar{x}(1/k - 1) + x$$

where x is the original variate and U is the transformed variate. With respect to the example shown in Figure 4, the transformation would have been $U = x + 0.58$. This transformation is shown by the upper curve in Figure 4.

The idea of rectifying skewed frequency data was introduced by *Goodrich* [1927] and has since been recommended as a visual fitting procedure [*Sub-Committee of the Joint Division Committee on Floods*, 1953].

Acknowledgments—This watershed-hydrology research project is maintained by the Agricultural Research Service, U. S. Department of Agriculture, in cooperation with the Ohio Agricultural Experiment Station, Wooster, Ohio. The author wishes to thank J. L. McGuinness for his assistance during the course of this study.

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Seismological Studies of the Western Rift Valley of Africa*

GEORGE H. SUTTON AND EDUARD BERG

Abstract—Intensity, strain release, and first-motion studies of earthquakes along the Western Rift Valley of Africa, using data from the seismograph network of the Institut pour la Recherche Scientifique en Afrique Centrale in the eastern Belgian Congo, during the period from May 1953 to April 1956 are presented. Regions of activity shifted during the period of observation, an increase in activity west of Lake Albert in July 1956 being especially noticeable. Intensity maps for three earthquakes show an elongation of isointensity regions parallel to the Rift. The rate of strain release in the area increased with the commencement of the Lake Albert shocks, changing from 35×10^8 ergs$^{1/2}$ to 155×10^8 ergs$^{1/2}$ per 100 days. Strain released during several aftershock sequences was proportional to the logarithm of the time after the initial shock.

First-motions from Rift Valley earthquakes to the stations of the Institut pour la Recherche Scientifique en Afrique Centrale (IRSAC) do not give a unique determination of the predominant type of faulting. The data are consistent with dip slip faulting along steeply dipping faults parallel to known faults in the region with motion such that the elevated areas are being further elevated and the depressed areas further depressed. They are also consistent with strike slip faulting along near-vertical faults with the eastern sides moving north. In agreement with the near station results, first-motion data from distant stations for two shocks west of Lake Albert indicate some combination of reverse dip-slip and sinistral strike-slip motion along a fault plane dipping toward the Rift Valley.

Introduction—The data presented here include (1) intensities and magnitudes; (2) aftershock strain release and regional strain release observations; and (3) first-motion observations of earthquakes in the vicinity of the Western Rift Valley of Africa.

The seismograph network of the IRSAC in eastern Belgian Congo, has been in operation since May 1953, at which time the station at Lwiro was put in operation. At the conclusion of the present study, three stations were operating: Lwiro, Astrida, and Uvira (Fig. 1). These stations form a triangle with sides approximately 120 km in length astride the Western Rift Valley. They have been described previously by *DeBremaecker* [1955]. During the period covered by this study each station was operated with a long and short period Benioff vertical and two short period Wood-Anderson horizontal seismographs.

One of the primary objectives of the IRSAC network is to study the seismic activity associated with the faulting and volcanism of the Western Rift Valley. The present paper includes results of observations in this region during the three-year period from May 17, 1953 to April 1, 1956. Most of the detailed observations were obtained during the period April 5, 1955 to April 1, 1956 when all three stations were in operation.

Earthquake intensities have been determined mainly through questionnaires returned from territorial administrators in the Congo and Ruanda-Urundi under a routine program established by DeBremaecker. Intensity data from British East Africa have been obtained with the cooperation of the East African Meteorological Service and were available for only the last six months covered in this paper. Modified Mercalli scale intensities and Richter magnitudes using the Wood-Anderson torsion seismographs as standard have been used in this study.

Intensity observations—The locations of maximum intensity for reported earthquakes during the period April 6, 1955 to April 1, 1956 are shown in Figure 1. The hachured areas are those from which earthquakes were reported felt during the period May 1953 to April 5, 1955 [*DeBremaecker*, 1955]. The largest earthquakes during the later period occurred west of Lake Albert and east of Lake Tanganyika. These areas were relatively quiet during the earlier period. The effect of the activity in these areas on the regional rate of strain release will be discussed below.

Figure 2 is an isointensity map for the shock of July 22, 1955 near the west shore of Lake Albert. The intensity data from this shock are the most complete of any of the Rift Valley shocks studied to date at IRSAC. The instrumental epicenter and isointensity lines locate the focus near the

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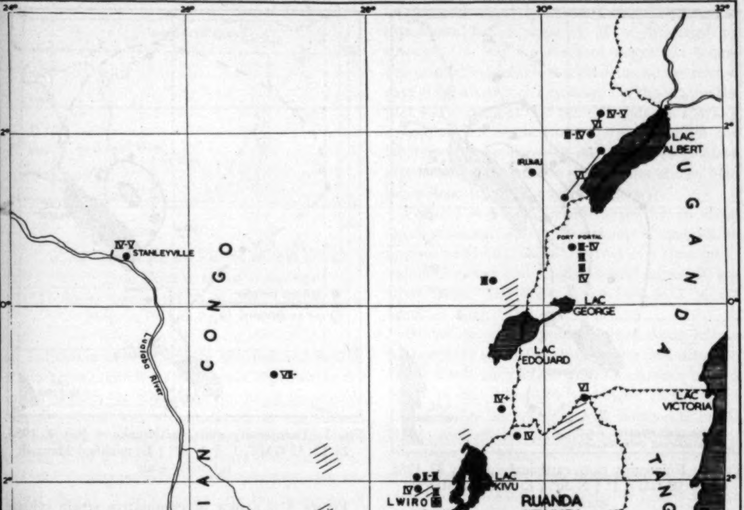
* Lamont Geological Observatory (Columbia University), Contribution No. 274.


24°
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32°
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BELGIAN CONGO
UGANDA
TANGANYIKA TERRITORY
RUANDA URUNDI
STANLEYVILLE
Lualaba River
LAC ALBERT
IRUMU
FORT PORTAL
LAC GEORGE
LAC EDOUARD
LAC VICTORIA
LAC KIVU
LWIRO
BUKAVU
ASTRIDA
UVIRA
USUMBURA
LAC TANGANIKA
● LOCATIONS REPORTING MAXIMUM INTENSITY
▨ DISTURBANCES REPORTED BEFORE 6 APRIL 1956 (DE BREMAECKER 1955)
☐ I.R.S.A.C. SEISMIC STATIONS

FIG. 1 – Earthquake intensities, April 6, 1955 to April 1, 1956; modified Mercalli intensity scale

rift wall west of Lake Albert. Elongation of isointensity lines parallel to the structure is evident. Maximum intensity was VI Mercalli units and the magnitude recorded at Lwiro was 6.0.

An isointensity map for the shock of September 4, 1955, also near the west shore of Lake Albert, is shown in Figure 3. Again, there is some indication of elongation parallel to the structure for the higher intensity contours although this is not as definite as in the preceding example. There is some offset between the (IRSAC) instrumental epicenter and the region of maximum intensity. The USC&GS epicenter puts the shock on the eastern side of the rift. The intensity data indicate that the IRSAC epicenter is probably more nearly correct and that the faulting was on the western side of the

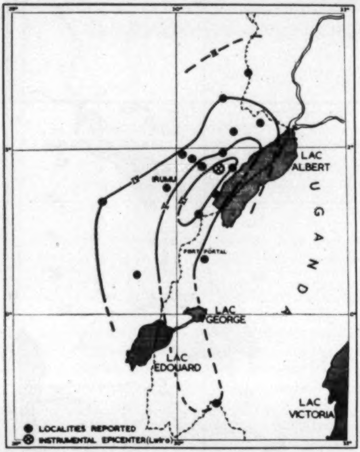

LAC ALBERT
U G A N D A
IRUMU
FORT PORTAL
LAC GEORGE
LAC EDOUARD
LAC VICTORIA
LOCALITIES REPORTED
INSTRUMENTAL EPICENTER(Lwiro)

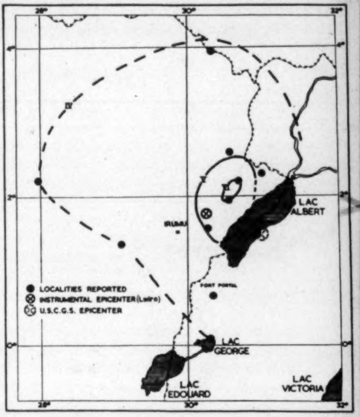
FIG. 2 – Isointensity map, earthquake of July 22, 1955, 04:00:03 GMT, 1° ¾ N 30° ½ E; modified Mercalli intensity scale

rift. Maximum intensity for this shock was VI and the magnitude at Lwiro was 6.3.

This and the previous shock have been used in a first-motion study of the nature of faulting, as interpreted from distant station observations by the Byerly-Hodgson method, and will be discussed below.

Figure 4 is an isointensity map for the shock of February 3, 1956 east of Lake Tanganyika near the border between Urundi and Tanganyika Territory. Again, the isointensity lines roughly parallel the structure. The maximum reported intensity was VI. However, there is no closure of the isointensity lines and greater intensities might have been reached further east or south. The magnitude at Lwiro for this shock was 5.5.

Strain release—Following the method of *Benioff* [1951], the square root of the seismic energy J was calculated using the relation $\log J^{\frac{1}{2}} = 4.5 + 0.9 M$, where M is the magnitude. (This equation has been superseded [*Gutenberg*, 1956], but was used here in order to facilitate comparison of our results with those of Benioff.) The summation of the $J^{\frac{1}{2}}$ was plotted against time. Assuming a linear relationship between the energy and the square of the strain, the square root of the energy is proportional to the strain, and a plot of cumulative $J^{\frac{1}{2}}$ against time will give the rate of strain release.


28°
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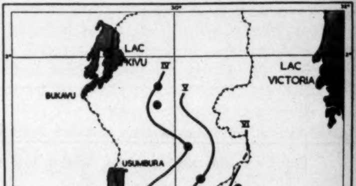
INSTRUMENTAL EPICENTER(Lwiro)
U.S.C.G.S. EPICENTER
LAC GEORGE
LAC EDOUARD
LAC VICTORIA

FIG. 3 – Isointensity map, earthquake of July 4, 1955, 22:12:52 GMT, 1° ¾ N 30° ¼ E; modified Mercalli intensity scale

Figure 5 is a plot of cumulative strain release through Rift Valley earthquakes of magnitude 3.0 or greater during the three-year period of observation. Two rates are indicated, 35×10^8 ergs$^{\frac{1}{2}}$/100 days and $155 \times$ ergs$^{\frac{1}{2}}$/100 days. The higher rate is a reflection of the increased activity west of Lake Albert and east of Lake Tanganyika mentioned earlier. Also, many more intensity cards were returned during this period than previously.

The time duration studied is probably too short to consider the change in rate of strain release as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BUKAVU
IV
V
VI
LAC VICTORIA
USUMBURA
LAC TANGANIKA
LOCALITIES REPORTED
INSTRUMENTAL EPICENTER(Lwiro)

FIG. 4 – Isointensity map, earthquake of February 3, 1956, 21:38:00 GMT, 4°S 30° ½ E; modified Mercalli intensity scale

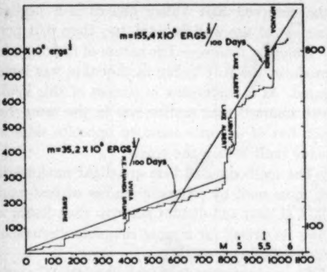

FIG. 5 – Strain release, Rift Valley earthquakes, from May 17, 1953 to April 1, 1956

an indication of a change in the regional rate of strain accumulation. It is possible that during the earlier period, the strain was not being released as efficiently and was accumulating in the crustal material at a greater rate than during the later period. Some downward curvature is noticeable on the plot during periods immediately following the larger shocks. This is caused by the influence of aftershock sequences of the larger shocks on the regional strain release. When plotted against a logarithmic time scale these portions approximate straight lines.

Figure 6 shows the rate of strain release from two Uvira aftershock sequences. The time scales are logarithmic. All of the observed shocks are included on these plots and, since our Uvira station was only a few kilometers from the epicenters, magnitudes down to about 0.5 are included. The shock of July 3, 1954, initiating the first series, was of magnitude 5.5 and had a maximum intensity of about VII near Uvira. The straight line shown has a slope of 35 × 10⁷ ergs½/log t(hours). On July 4 a shock of magnitude 4 near the original epicenter disrupted the strain release rate of the aftershock sequence. For this reason the plot was stopped at that time. On July 5 a shock of magnitude 4.5 at the same epicenter, within our location error, apparently started an independent aftershock sequence. The straight line shown here has a slope 16 × 10⁷ ergs½/log t(hours).

Figure 7 is a strain release graph for an aftershock sequence following two shocks of magnitudes approximately 4½ which occurred at a time interval of 13 minutes on August 3, 1955, about 20 km from Uvira. The slope shown here is 3 × 10⁶ ergs½/log t(hr).

Benioff has interpreted aftershock strain release proportional to the logarithm of the time after the initial shock, such as has been shown here, to be a result of the liberation of elastic creep strain stored in the surrounding rock before the initial shock, through the action of compressive or tensional stresses. Many of the shocks used here are considerably smaller than those based on previous studies of this kind. However, the results appear to be quite similar to those previously obtained.

The number of shocks recorded during the three-year period of observation, in each magnitude interval of 0.5 units, from magnitude 3 to 6.5, was counted. The results are shown in Table 1. The result of a plot of log N against M gives a fairly well determined straight line of slope −0.6. This logarithmic dependence has been found in aftershock sequences, regional earthquake studies, and global earthquake studies by other investigators. *Gutenberg* and *Richter* [1954] and *Gutenberg* [1956] in a more recent paper give a value of −0.9

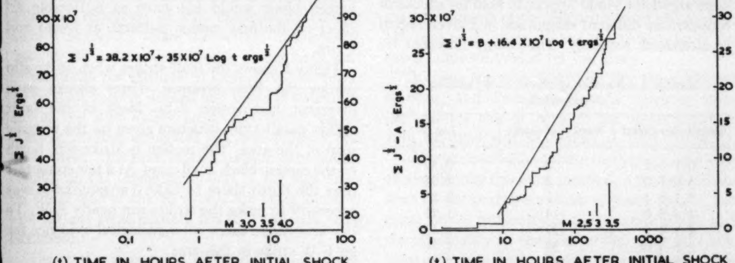

FIG. 6 – Strain release, Uvira aftershocks: starting July 3, 1954 (on left); starting July 5, 1954 (on right)

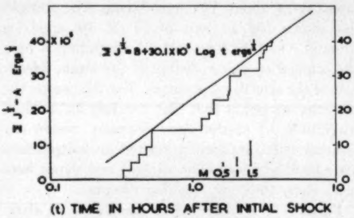

FIG. 7 – Strain release, Uvira aftershocks, starting August 3, 1955

with a small standard deviation for shallow shocks. One possible explanation for the low value found here is that the observation radius of the African stations decreases with decreasing magnitude and a larger area is monitored for the large shocks than for the smaller shocks. This same reasoning would apply on a world-wide scale for shocks below a magnitude of about 5.5 or 6, recording of which would be dependent upon location relative to the world's seismograph stations.

The total strain release over the three-year period from the Rift Valley shocks was about 8.5×10^{10} $\text{ergs}^{1/2}$, equivalent to an average rate of 2.8×10^{10} $\text{ergs}^{1/2}$/year. Benioff, using the same energy equation, has obtained a rate of about 80×10^{10} $\text{ergs}^{1/2}$/year for the strain release from all great earthquakes, magnitude 8 or greater, over a fifty-year period. Thus, the Rift Valley rate is about 3½ pct of that for the world's great earthquakes. This rate appears to be much too high. The 'constant' factor relating the square root of the energy to the strain contains a volume term which undoubtedly changes with magnitude, probably to a sufficient degree to make a direct comparison between the rates meaningless. The same argument would appear to hold for shocks of considerably different magnitude in a given region or aftershock sequence. The energy liberated by the observed Rift Valley quakes is a negligible portion of the world's total, less than 0.01 pct.

TABLE 1 – *Number of shocks as a function of magnitude*

Magnitude interval	Number of shocks	Log N
6.1–6.5	2	0.30
5.6–6.0	3	0.48
5.1–5.5	7	0.85
4.6–5.0	14	1.15
4.1–4.5	27	1.43
3.6–4.0	57	1.76
3.1–3.5	124	2.09

Nature of faulting—The nature of faulting which produces the Rift Valley earthquakes was investigated. As is customary in studies of this kind, it was assumed that motion was in the same direction but of opposite sense on opposite sides of a plane fault within the crust.

The methods used here are slight modifications of those used by others in studies of first-motion data at near and distant stations. (See *Sutton* and *Berg* [in press], for a more complete discussion of the methods.)

The near-station data from the IRSAC stations were interpreted using two different assumptions: (1) vertical faults with pure strike-slip motion; (2) near-vertical faults with pure dip-slip motion. In both cases fault strikes were drawn at the epicenter as near parallel the known faults in the area as possible, while keeping the first-motion data consistent with the assumed fault motion. The tectonic map of the Belgian Congo by *Cahen* [1952] was used for this purpose.

Under the dip-slip assumption a change in direction of first-motion would be expected when Pn becomes the first arrival [*Gutenberg*, 1941]. To account for this effect, circles were drawn around the stations at this critical distance and the first-motion within a circle was reversed for the station in question. To account for the first-motion at Astrida from a number of shocks under and near Lake Kivu, it was necessary to cut off the critical circle along a line roughly parallel to the structure in the area. This is approximately equivalent to assuming that the faults in the Lake Kivu area dip E S E at between 75° and 80° (assuming a focal depth of about 15 km). Because of the distribution of epicenters, and changes in fault strikes along the Rift Valley, a similar dip toward the graben block would not have as noticeable an effect on the first motion patterns at Lwiro and Uvira.

Figure 8 shows the fault strikes when strike-slip motion has been assumed. Three shocks gave divergent first-motion data. Most of the fault strikes parallel the structure given on the tectonic map of the area. The motion is strike-slip, north on the eastern block in all cases. At a few epicenters near the north shore of Lake Tanganyika it was necessary to make the strikes run nearly E-W. To our knowledge there is no geological evidence for an E-W strike in this area.

Figure 9 shows the fault strikes when dip-slip

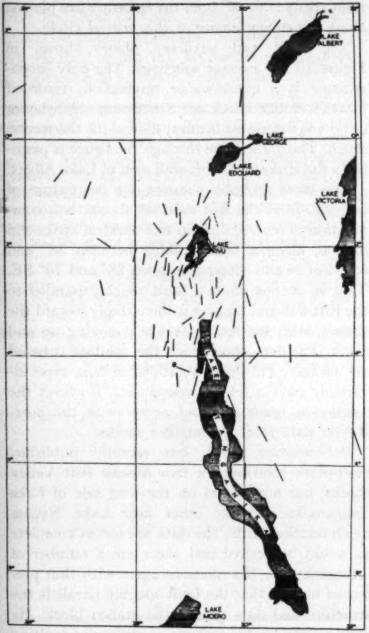

FIG. 8 – Fault strikes assuming strike-slip faulting, north on eastern side; each line represents one or more earthquakes; dashed lines indicate divergent data, solution obtained by disregarding data from one station.

motion is assumed. Here there were two cases where the data were divergent. The resultant motion pattern can be separated into five regions, with the exception of two earthquakes east of Lake Tanganyika where the motion was opposite that for the surrounding shocks. Going from west to east near the latitude of Lake Kivu, we have: up on west (poorly defined and possibly independent of the Rift Valley tectonic pattern); up on east; up on west, up on east (not well defined); and up on west. This fault motion pattern corresponds roughly to the topography; that is, the high areas on either side of the Rift walls are being elevated and the low areas between the Rift walls are being depressed.

The fault strikes south of Lake Kivu are somewhat distorted. However, the Kivu area is more complicated than portions of the Rift Valley to the north and south. The eastern Rift fault may be missing in this area and the graben block is at a higher elevation. There is a difference in elevation of about 700 m between the levels of Lake Tanganyika and Lake Kivu. Part of the apparent uniformity of the results for the more distant shocks may be a result of the insensitivity of the method for some of the more distant shocks because of the small angle subtended by the array.

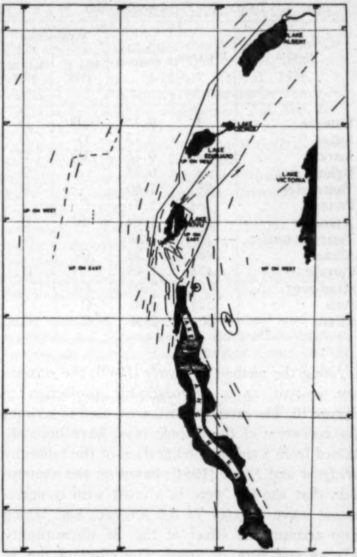

FIG. 9 – Fault strikes assuming dip-slip faulting; each line represents one or more earthquakes; dashed lines indicate divergent data, one station omitted from solution.

Thirteen stations, including the three IRSAC stations, and Entebbe, Uganda, reported first-motions for one or both of the earthquakes of July 22, 1956 and September 4, 1956 (Table 2).

As mentioned before, these earthquakes occurred at very nearly the same location, a few kilometers west of the northwest shore of Lake Albert. Because of the proximity of the two epicenters, and the consistency of the first-motion data from stations reporting both shocks, the two shocks have been treated as one.

TABLE 2 – *First-motion data*

Station	Distance	Extended distance	First-motion	
			Sep. 4, 1955	July 22, 1955
	°			
Entebbe	3	0.75	cD	D
Lwiro	4½	0.75	D	D
Astrida	4½	0.75	D	D
Uvira	5	0.75	...	D
Tananarive	28	1.60	...	D
Pretoria	28½	1.61	C	...
Jerusalem	30	1.64	dC	D
Tammenrasset	32	1.69	...	C
Alicante	46	1.92	C?	...
Cartuja	47½	1.95	...	C
Strasbourg	50½	2.02	D?	...
Paris	52½	2.07	C	...
Kiruna	66	2.49	C	C

Using the method of *Byerly* [1942], the stations are plotted on a stereographic projection in Figure 10. The extended distances, used to account for curvature of the seismic rays, have been obtained from a simple modification of the tables by *Hodgson* and *Storey* [1954]; based on the assumption that the foci were in a crust with compressional wave velocity of 6.5 km/sec, and taking into account the effect of the *M* discontinuity (*Sutton* and *Berg*, in press]. The effect of the *M* discontinuity on the extended distances for stations at distances between that for which *Pn* becomes the first arrival and about 10° is to create a critical circle around the epicenter whose radius is a function of the critical angle for *Pn*. Stations from about 1° to 10° from the epicenter are plotted along the circumference of this critical circle.

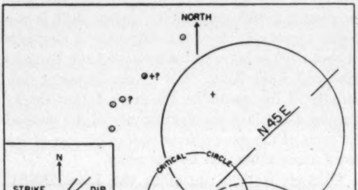

FIG. 10 – First-motion, shocks of July 22 and September 4, 1955, 1° ¾ N, 30° ½ E

The fault and auxiliary planes shown in Figure 10 are average solutions. The only inconsistency is a questionable rarefaction, recorded for the earlier shock at Strasbourg. Strasbourg could not determine the first motion for the second shock. The dashed line through the figure is parallel to the strike of the rift wall west of Lake Albert.

The most probable solution for the nature of faulting, from the first motions shown, is a combination of reverse dip-slip and sinistral strike-slip motion, along a fault striking between 38° and 66° E of N and dipping between 58° and 70° SE. That is, motion along a fault roughly parallel to the Rift wall and dipping rather steeply toward the graben, with the southeast block moving up and north. The data upon which this solution is based are meager. Published solutions of this type invariably have a few inconsistencies. However the solution is reasonable and agrees with the near-station data from the smaller shocks.

DeBremaecker [1956] has recently published fault-plane solutions for two African Rift Valley shocks, one near Uvira on the west side of Lake Tanganyika and the other near Lake Nyassa much further south. The data are not as complete as would be desired and there are a number of inconsistencies. His solutions agree with that presented here in that the fault roughly parallels the structure and dips toward the graben block. He finds a considerable amount of strike-slip faulting combined with normal dip-slip in one case and reverse dip-slip in the other.

Conclusion—The data presented here give some information about the tectonic activity in the interesting Rift Valley region of Africa. They indicate that the present earthquake activity is located along faults which in most cases are parallel to the Rift walls. Isointensity lines are elongated in these same directions. Limited data indicate fault dips toward the graben block. The average direction of faulting could be strike-slip, north on the eastern side or dip-slip with the upwarped marginal ridges being further uplifted and the graben block further lowered, or some combination of the two. If the logarithmic rate of aftershock strain release is indicative of tensional or compressional elastic creep strain this would presumably favor the dip-slip interpretation.

The rate of strain release increased by a factor of 5 about July 1956. This change was coincident with the commencement of activity west of Lake

Albert and east of Lake Tanganyika. A longer observation period is probably necessary to determine whether or not this represents a change in the regional rate of strain accumulation.

Acknowledgments—The research reported here was made possible by a William Bayard Cutting Traveling Fellowship from Columbia University and a Belgian-American Educational Foundation Fellowship which enabled the first author to exchange positions with J. Cl. DeBremaecker as seismologist at IRSAC for one year. The cooperation of the East African Meteorological Service and the seismologists who kindly supplied data used in this study is gratefully acknowledged.

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Short-Period Oceanic Surface Waves of the Rayleigh and First Shear Modes*

JACK OLIVER AND MAURICE EWING

Abstract—Waves corresponding to the short-period segment of the Rayleigh mode and to the first shear mode are identified for paths traversing the deep ocean, apparently for the first time. It appears that the reason for the presence of the waves in this case and their conspicuous absence in all other cases is that (a) the shock which excited these waves is the atomic explosion of Operation Wigwam, deep in the Pacific Ocean; (b) earthquake sources are generally too deep to excite short-period surface waves efficiently. The new data strongly support the normal mode explanation for the dispersion of Rayleigh waves crossing the Pacific Ocean and furnish supporting evidence for the crustal structures previously deduced from surface wave dispersion and from refraction shooting. The unusual characteristics of the body phases and the *T* phase may probably be explained, as well, by assuming the source was within the water layer.

Introduction—A group of seismograms of unusual appearance was recorded at Palisades from the shock of May 14, 1955 in the Pacific Ocean off Lower California. The U. S. Coast and Geodetic Survey placed the epicenter at 29°N, 126½°W, the time at 20h 00m 00s GMT. Although no magnitude has been reported, the Bulletin of the Bureau Central International de Seismologie (Strasbourg) gives arrival times for *P*, *S*, and other body phases for 54 stations from every continent except Antarctica. Upon inspection, records from several west coast and Hawaiian seismographs also revealed unusual characteristics, some similar to those at Palisades. Three striking effects were noted: (1) a prolonged oscillatory and very nearly sinusoidal character in the body waves, *P*, *PP*, and *S*; (2) a surface wave train of the Rayleigh type of surprisingly long duration and including waves of short period in an unusual dispersive pattern; a *T* phase of extremely large amplitudes at the west coast and Hawaiian stations.

A more detailed investigation revealed that the major parts of the surface wave trains could be explained satisfactorily as the result of normal mode propagation in the oceanic and continental structures along the path. For the oceanic segment, however, it was found that modes and portions of modes of propagation had been excited which had never before been observed from an earthquake source. In fact, the excitation was such that an extremely shallow source, possibly within the water layer, seemed likely. Since a source so located could also account for the other observed features, it seems almost certain that this particular shock is the deep atomic explosion of Operation Wigwam which was reported to have been detonated in the area sometime during May 1955. That the epicenter is not in a seismic belt and that the time of occurrence falls on an even hour (12 noon PST) support this view very nicely.

Regardless of the nature of the source, this shock is a very important one to the study of surface wave propagation over oceanic paths since it excited two types of surface waves which had not previously been found to propagate along oceanic paths. One type corresponds to the short-period branch of the Rayleigh wave curve computed from a crustal model deduced from seismic refraction results and from the analysis of the long-period Rayleigh waves. The second type corresponds to the next higher mode, here called the first shear mode. These observations prove that the absence of short-period Rayleigh waves on earthquake seismograms for oceanic paths does not require a major revision of the present structural model.

Once the dispersion for the oceanic portion of the path is understood, the explanation for the Palisades surface wave train follows readily. The train consists primarily of waves crossing both the oceanic and continental portions of the path in the fundamental Rayleigh mode. The slow velocity of some of the waves is the result of propagation near the group velocity minimum in both cases.

EXPERIMENTAL DATA

Surface waves—Figure 1 shows the surface wave portion of the Palisades seismogram of this shock. Instrumental constants and the time correction are also shown. The record contrasts greatly with Palisades seismograms of west coast shocks in that (a) the duration of the directly arriving surface wave train is much greater than usual and (b)

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* Lamont Geological Observatory Contribution No. 290.

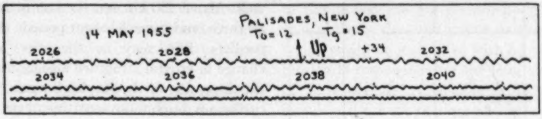

FIG. 1 – Palisades seismogram, surface waves

short period, large amplitude waves of the Lg type are absent. Since this shock is farther offshore than most shocks in the vicinity of the west coast, records from the Berkeley, Fresno, and Pasadena stations were examined in an effort to isolate the effect of the oceanic portion of the path. Surface wave dispersion at these stations is plotted in Figure 2. Standard surface wave analysis techniques have been used [*Ewing* and others, 1957]. When the wave trains are irregular the period has been obtained by measuring over a few cycles of a group. The Berkeley and Pasadena data obtained in this manner are in good agreement.

Also shown in Figure 2 are theoretical curves of group velocity versus period for the Rayleigh and first shear modes for a crustal structure typical of the deep oceans. The structural model used is also shown in Figure 2, where α is the compressional wave velocity, σ is Poisson's ratio, and H is the thickness of the upper and the intermediate layers. The fit of the data to the curves is generally very good and is the chief basis for the wave identification. Waves corresponding to the segment of the Rayleigh mode in which the periods decrease with decreasing velocity are present, as is normally the case with earthquake sources. In addition, however, waves corresponding to the group velocity minimum and to the short-period segment of the curve in which periods increase with decreasing velocity are present. Furthermore, some waves which clearly correspond to the first shear mode are also present. Waves corresponding to this mode and to the short period segment of the Rayleigh mode, with the exception of the T phase, have never been identified in the case of earthquake sources.

It has been suggested that the reason for the absence of these waves is the depth of the source. Theoretical calculations [*Press* and others, 1950] have shown, as one might determine intuitively, that as the depth of the source beneath the ocean bottom is increased, the relative excitation of the shorter waves diminishes much more rapidly than that of the longer waves. With this hypothesis, however, it is necessary to rely on topographic effects near the source to account for the excitation of the T phase by earthquakes. Alternative proposals are that waves in the short-period range suffer great attenuation, possibly by absorption or by scattering, when traversing oceanic paths, or that some presently unknown but wide-spread crustal feature affects propagation of waves in this period range strongly.

The present data indicate that, for the path under study, attenuation is not of major importance to dispersion studies and that variations from the assumed crustal structure are small. The fact that the short-period waves are strongly excited implies a very shallow source, and the data appear to be in agreement with a source in the water layer. This deduction is based on comparison with theoretical calculations and experimental data from countless earthquakes.

The experimental data of Figure 2 establish the thickness of the liquid layer of the theoretical structures at about 4.5–4.6 km. Since this layer is meant to include both the water and unconsolidated sediments the average thickness of the sediments can be found by subtracting the mean water depth along the path from the liquid-layer thickness [*Ewing* and others, 1957]. This gives a value between 0 and ¼ km for the sediment thickness. A refraction profile by *Raitt* [1956; M_1 in his notation] at one point in the area gave 0.26 km for sediment thickness, in good agreement.

At the long-period end of the spectrum, points corresponding to the Rayleigh mode are slightly low. This might be expected if the crustal structure is slightly modified from that typical of the deep

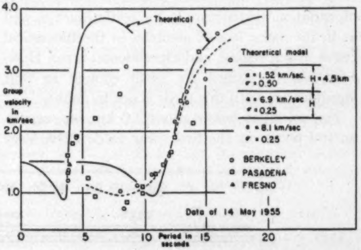

FIG. 2 – Surface wave dispersion over oceanic portion of path

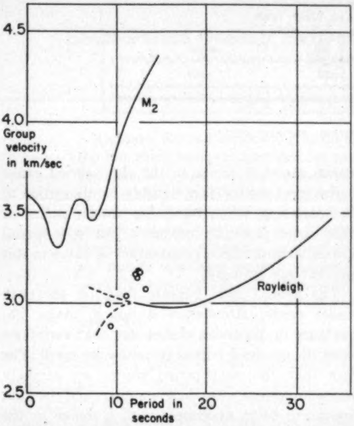

FIG. 3 – Surface wave dispersion over continental portion of path

ocean as the mean water depth, smaller than average for the oceans, would suggest. Raitt's profile lends support to this idea. It is encouraging that the velocity tends to be slightly slower, if anything, to Berkeley than to Pasadena, indicating a little more departure from the typical oceanic crust. This is just what would be expected from the bottom topography of the area, the depth along the path to Berkeley being, on the average, slightly less. No corrections have been made for the continental portion of the path, however, and there is always the possibility of an error in epicenter location, so this point is somewhat speculative.

Near and to the left of the minimum, points corresponding to the Rayleigh mode also deviate slightly from the theoretical curve. This may be the result of many influencing factors including effects of variation in structure in the water layer as well as in the rocks, loss of precision in the theoretical curve in this region, and experimental error. However, the deviations are small enough so that identification with this mode is not in doubt.

For velocities below about 2.0 km/sec, experimental points fit the first shear mode curve very well. Above 2.0 km/sec the points are sparse, but all three tend toward longer periods than the curve predicts. This may be the effect of the small change in crustal structure also required to satisfy the dispersion of the Rayleigh mode. Higher mode curves are much more sensitive to small changes in structure. Extensive calculations which the data do not warrant would be required to make certain of this. It does appear certain, however, that waves corresponding to at least a portion of the first shear mode have propagated along the oceanic portions of the paths between the epicenter and Pasadena and Berkeley. Propagation in this mode had been suggested previously but no certain identification had ever been made of these waves or of the short-period waves of the Rayleigh mode in the deep ocean prior to the present study. Waves of a similar nature, however, are frequently found in shallow water studies where the source is an artificial one located in the water layer.

The dashed line of Figure 2 is the experimentally determined dispersion curve for waves in the Rayleigh mode. Using this curve to obtain the travel times over the oceanic portion of the path, the dispersion curve for waves crossing the continental portion can then be easily deduced from the Palisades data. The results are shown in Figure 3. The waves appear to have crossed the continent in the Rayleigh mode rather than one of the higher modes, and the periods recorded correspond largely to the broad flat portion of the Rayleigh mode curve of earthquake-generated continental surface waves. The curves shown for the Rayleigh and M_2 modes are experimental ones found in earlier studies [*Oliver* and *Ewing*, 1958]. Thus most of the dispersion at Palisades is due to the oceanic rather than the continental segment of the path. Although there is some uncertainty in the points of Figure 3 because the exact length of the ocean path is somewhat in doubt, it is not possible to vary this length enough to affect the identification. The length of the oceanic segment used for the points shown was 800 km. It is interesting that there appears to be a slight 'tailing off', that is, slowing, at periods of about ten seconds. This phenomenon has frequently been noticed in studies of earthquake waves from west-coast shocks. It is not yet completely understood but may be the effect of the

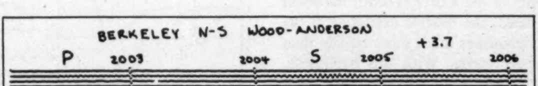

FIG. 4 – Berkeley seismogram, body waves

surficial sedimentary layers on the Rayleigh wave propagation. It is clear from the measured velocity, however, that the waves have crossed the continent in the Rayleigh mode.

T Phase—Exceptionally large *T* phases were recorded by the California station and according to newspaper reports, felt along the California coast. At Hawaii, virtually the entire seismic effect was a *T* phase of large amplitude. A notation on the seismogram indicates that it was felt on northeast Oahu and hence misinterpreted originally as a local earthquake.

T phases may be thought of as waves of very short period (<1 sec) propagating as one or more of the normal modes, although these modes, as shown in Figure 2, might be modified very slightly in this period range by the velocity structure of the water and sediments.

In addition to the wave guide effect due to the gross crustal structure, *T* phase propagation is aided greatly by the sound channel within the water, that is, the sofar channel [*Ewing* and others, 1957]. Earthquakes frequently excite *T* phases in spite of their depth beneath the surface, an effect usually attributed to topographic irregularities. However, the relative amplitudes in the present study are so large that a source within the water layer, possibly very near to the axis of the sofar channel is strongly suggested.

That Operation Wigwam excited strong *T* phases is evident from the study based on these waves by *Sheehy* and *Halley* [1957]. They studied the attenuation of sound in water using reflected *T* phases and found arrivals with travel times up to nearly four hours. They did not, however, publish the date, time, and exact location of the test. They do give the arrival times, but not the date, of *T* phases at west coast and Hawaiian stations. These times are in excellent agreement with the origin time of 20h 00m 00s GMT and the location given by the U.S.C.&G.S. Sheehy and Halley also state that the test shot of Operation Wigwam was fired in the deep sound channel.

Body phases—The body phases *P*, *PP*, and *S* show a pronounced oscillatory character of long duration wherever recorded (Fig. 4). The *S* phases consist almost entirely of waves having periods of about 2.4 sec. This period is most prominent in the *P* and *PP* phases but these also include waves of about a 1.3-sec period. Records from the short-period seismographs show periods of about 0.75 sec and possibly some that are even shorter, but the unusual long oscillatory character is due primarily to the 2.4- and 1.3-sec waves. Since waves of this period are not prominent in the *T* phase, it is unlikely that the source or the bubble pulse which would be associated with an underwater explosion is responsible for the long trains of waves of these periods. A possible explanation may be found in the work of *Burg* and others, [1951] who found waves of prolonged sinusoidal character in seismic prospecting records taken in a water-covered area. Essentially, they attribute these 'tones' to standing waves in the water layer which leak gradually into the substratum. Using the liquid-layer depth found in the section on surface waves, it can easily be determined that periods of 2.4 and 1.3 sec correspond almost exactly to the third and fifth normal modes. Why these modes should be excited and not the others probably depends on condition at the source, possibly on the spectrum at the source when the bubble pulses are included. In favor of this hypothesis is a slight decrease in period in the long *S* wave train at Berkeley, as predicted by the analysis of *Burg* and others. It is apparent that body-wave data do not conflict with the placement of the source within the water layer. A more thorough study of this portion of the seismograms would require information on the source and location which is not generally available.

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Velocity of Seismic Waves in the Earth's Mantle*

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Abstract—On the basis of our present knowledge the Earth's mantle may be divided into four sections: (a) from the Mohorovicic discontinuity to a depth of about 200 km, with small changes in the wave velocities which have minima in this section; (b) from 200 to 950± km with relatively rapid, fairly regular increase in velocity; (c) from 950 to 2700± km with smaller and less regular increase in velocity; almost straight line portions of the travel-time curves and relatively small wave amplitudes at certain ranges of distance indicate at least two portions of (c) where the wave velocity increases relatively little with depth; (d) from 2700 km depth to the core boundary with little change in velocity and probably maxima roughly 100 km above the core boundary.

Bullen [1953, p. 209] has divided the Earth's interior into regions of which B, C, and D constitute the Earth's mantle. New data on travel times and amplitudes as function of the epicentral distance have made it advisable to attempt a revision of this division. It is now believed widely that the velocities of P and of S do not change much and partly decrease in the upper 200 ± km of the mantle, and probably reach minima at depths between 100 and 200 km. On the other hand, no evidence seems to exist any longer for a first or second order discontinuity at a depth near 400 km. This discontinuity had been found on the assumption that the velocities increase everywhere in the upper mantle, and effects of the layer with relativity low velocity near the top of the mantle had been attributed to the nonexisting discontinuity at 400 ± km depth.

To find the velocity in the mantle as a function of depth, effects of all irregularities above 200 km must be eliminated by calculation, and the usual procedure to obtain velocities must be applied to this hypothetical Earth. The velocities v_s of P and S as function of the depth r_s can then be based on Wiechert's equation [*Wiechert* and *Geiger*, 1910]

$$\log r_s = 3.80393 - 0.0024127 \int_0^{\Theta_s} q \, d\Theta \qquad (1)$$

where cosh q is the ratio of the apparent velocity $\bar{v}_s$ at the angular distance Θ_s to all corresponding values of $\bar{v}$ between $\Theta = 0$ and $\Theta = \Theta_s$. The velocity v_s at the distance r_s from the Earth's center is given by

$$v_s = r_s \bar{v}_s / r_0 \qquad (2)$$

r_0 = Earth's radius. If $\bar{v}$ changes rapidly with distance, the velocity increases rather rapidly with depth at the depth r_s where the ray emerging at Θ_s has its deepest point; if the travel time curve is nearly straight near Θ_s, the change in velocity at the corresponding depth r_s is relatively small.

Another way to find information on changes of velocity with the depth r_s is based on the change in amplitudes of a given phase with the distance Θ_s. The amplitude a (in microns) of a body wave (period T) arriving at the distance Δ in a shock of magnitude m may be expressed to a first approximation [*Gutenberg*, 1945] by

$$\log(a/T) = m - A \qquad (3)$$

where m is the unified magnitude of the shock [*Gutenberg* and *Richter*, 1956]. For shallow shocks

$$A = 6.3 - \log B - \tfrac{1}{2}[\log C + 0.43\, kD + \log \tan i_0 + \log |di/d\Theta| - \log \sin\Theta] \qquad (4)$$

The value 6.3 is an empirical constant which depends on the definition of m and is practically equal for P- and S-waves [*Gutenberg*, 1945, p. 61]; B is the ratio of the ground amplitude in the observed wave to the incident amplitude; B depends only on the wave type and the angle of incidence i_0 at the surface; Θ is the angular epicentral distance; C is the product of the ratios of the amplitude of the reflected or refracted wave to that of the incident wave at discontinuities; for values of B and C, see *Gutenberg* [1944]; for P and S it may be assumed that $C = 1$, neglecting the effects of discontinuities in the crust and of the Mohorovicic discontinuity. D is the distance along the ray; for P, PP, and S within the limits of errors kD may be replaced by $k\Delta$; k is the coefficient of absorption for the energy; $k = 0.12$ per 1000 km [*Gutenberg*, 1945, p. 58]. It does not depend noticeably on the periods of P and S for $\Delta > 2000$ km [*Gutenberg*, in press].

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* Contribution No. 853, Division of the Geological Sciences, California Institute of Technology, Pasadena, California.

The angle of incidence i_0 at the distance Δ (in km) is given by

$$\sin i_0 = v_0/\bar{v}_\Delta \qquad \bar{v}_\Delta = d\Delta/dt \qquad (5)$$

The selection of v_0, the velocity at the surface of the Earth, depends on the period of the waves since the wave lengths vary from a fraction to a multiple of the crustal thickness; for P, values of 6.1 as well as of 8.2 km/sec have been used, and for S values of 3.5 and 4.7 km/sec. The resulting calculated values of *A* are smaller by about 0.2 near $\Theta = 30°$ and by about 0.1 near 90° for the

TABLE 1 – *Values of log a/T calculated from (3) to (5) for v_0 = 6.1 km/sec for P and v_0 = 3.5 km/sec for S for a shock of magnitude m = 6; a = amplitude in microns, T = period in sec, i_0 = angle of incidence at the surface, θ = angular epicentral distance*

Vertical component of longitudinal waves P				Horizontal component of transverse waves S				Vertical component of longitudinal waves PP			
θ	i_0	$di_0/d\theta$	log a/T	θ	i_0	$di_0/d\theta$	log a/T	θ	i_0	$di_0/d\theta$	log a/T
°	°			°	°			°	°		
30	29	−0.32	−0.4	30	30	−0.25	−0.4	40	37	−0.65	−0.4
40	27	−0.15	−0.6	40	28	−0.35	−0.4	60	29	−0.16	−0.8
50	24	−0.24	−0.6	50	26	−0.20	−0.6	80	27	−0.08	−1.1
58	23	−0.08	−0.7	60	24	−0.22	−0.6	100	24	−0.12	−1.0
70	20	−0.25	−0.8	70	22	−0.20	−0.7	116	23	−0.04	−1.3
80	17½	−0.30	−0.8	80	19	−0.20	−0.8	140	20	−0.12	−1.1
90	14½	−0.15	−0.9	90	16½	−0.28	−0.8	160	17½	−0.15	−1.0
100	14¼	−0.02	−1.4	100	15¼	−0.10	−1.3	170	16	−0.18	−0.8

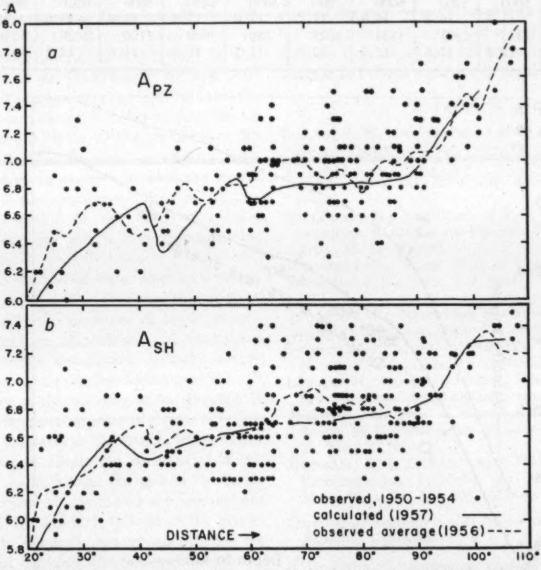

FIG. 1 – Values of *A* (a) for vertical component of *P*; (b) for horizontal component of *S*; observed values are calculated from (3) by using amplitudes *a* and periods *T* reported by 18 stations for shallow earthquakes of magnitudes *m*; calculated curves are based on travel time curves (4); the curves "Observed averages (1956)" are based on *Gutenberg* and *Richter*. [1956, Table 2]

vertical component of P, if $v_0 = 6.1$ km/sec instead of 8.2 km/sec. For S waves, an additional uncertainty arises from the fact that B depends on the direction of polarization. Fortunately, for angles of incidence between 0° and about 35°, log $B = 0.3$ within the limits of error regardless of the direction of polarization. If the velocity $v_0 =$ 3.5 km/sec, this is fulfilled for $\Theta > 22°$, that is, for all distances considered here; if $v_0 = 4.7$ km/sec, this is fulfilled only for distances over 50°. For small epicentral distances log B may vary appreciably with distance.

Table 1 contains selected calculated values for a/T on the assumption of travel times for a surface focus, for P by *Gutenberg* [1953], and for S by *Jeffreys* and *Bullen* [1948]. Corresponding calculated curves for A have been entered in Figure 1 and in similar other figures not reproduced including one for PP. They agree within the limits of error with the observations. It follows that the constant 6.3 in (4) is correct within about 0.2 units for P, PP, and S, and that consequently in earthquakes the same amount of energy, within a factor between $\frac{2}{3}$ and $1\frac{1}{2}$, enters into the longitudinal and the transverse waves.

Since there is no noticeable systematic divergence with increasing distance between the theoretical curves, all based on the same value of k, and the observed amplitudes it follows that k is roughly the same for P and S.

The amplitudes (Fig. 1) can be used to find depth ranges in the Earth where the velocity

TABLE 2 – *Apparent velocities $\bar{v}$ in km/sec, (a) calculated by Wiechert and Geiger [1910] from travel times at the distances Δ, corresponding depths d of the deepest points of the ray and corresponding velocities v_a for P; (b) values on the basis of travel times of Gutenberg [1953]*

Item	(a)					(b)					
Δ	4000	5000	5400	6000	7000	3890	4440	5000	6110	6670	km
$\bar{v}$	13.1	15.7	16.8	16.9	17.2	13.0	13.4	14.1	15.6	15.9	km/sec
d	996	1373	1521	1533	1625	880	980	1120	1420	1510	km
v_a	11.1	12.3	12.8	12.8	12.8	11.2	11.4	11.6	12.1	12.2	km/sec

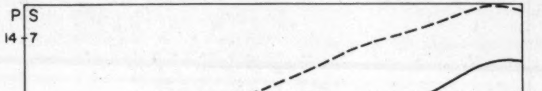

FIG. 2 – Velocity of longitudinal waves P and transverse waves S in the Earth's mantle

changes with depth faster or more slowly than average. If the travel-time curve is nearly straight, and the velocity does not increase much with depth, $|di/d\Theta|$ is small (Eq. 5), A in (4) is relatively large, and the amplitudes a are relatively small (3). Thus, relatively small amplitudes correspond to small increase (or even decrease) of velocity with depth at the deepest point of the ray. Similarly, large amplitudes indicate relatively large increase in velocity at the depth r_s. The investigation of changes in velocity with depth on the basis of observed amplitudes as function of epicentral distance [*Zoeppritz*, *Geiger*, and *Gutenberg*, 1912] is based on this fact.

Wiechert and *Geiger* [1910] made the first calculation of the velocity as a function of depth by use of (1) which they applied to travel time curves of Wiechert-Zoeppritz. Corresponding to their almost straight-line travel time curve section beginning at about $\Delta = 5400$ km ($\bar{v}$ almost constant, Table 2a) they found practically constant wave velocity downward from a depth of about 1500 km which Wiechert considered as the boundary of the core. However, it corresponds to the relatively straight line portions of the travel time curve which we find now (for example, *Gutenberg* [1953]) at distances from about 40° (4440 km) to 44° and from about 53° to 63° (compare (a) and (b) in Table 2). Newly calculated wave velocities as function of depth are shown in Figure 2. The beginning of the portion with smaller increase in velocity with depth was moved to a depth of 1200 km in the first attempt to use amplitudes in the determination of the structure of the Earth [*Zoeppritz*, *Geiger*, and *Gutenberg*, 1912]. It corresponds now to $d = 950$ km.

The original method of using amplitude ratios, especially PP:P, has the advantage that it gives relatively sharply the distances of nearly discontinuous changes in amplitudes, but errors are introduced by the assumption that the energy starting at the source in the direction of the PP ray is the same as that starting in the direction of P; moreover, the varying ratio of the wave length of PP to the thickness of the crustal layers at the point of reflection affects the constant C in (4). On the other hand, abrupt changes in curves for the average observed amplitudes are unintentionally replaced by gradual transitions in graphs like Figure 1. Similarly, travel-time curves are smoothed, and therefore the corresponding derivatives $d\Delta/dt$ can not show second-order discontinuities. Nevertheless, there is fair agreement now between ranges of distances, where the curvature of the travel time curve is small, and those where relatively small amplitudes are observed (compare Fig. 1).

Relatively regular changes in the slope of the travel-time curve and in the observed amplitudes at epicentral distances of less than 40° indicate that the relatively large increase of wave velocities between depths of about 250 and 900 km is fairly regular. However, in the deeper portion of the mantle, there are at least two sections, one between depths of 900 and 1000 km, another between 1400 and 1500 km (Fig. 2) where the velocity increases relatively slowly with depth (see $\bar{v}$ in Table 2 (b) and *Gutenberg* [1953, Table 2]).

The conclusion that both velocities decrease immediately above the core, is based on practically straight travel-time curves approaching the end of the curves for the direct P and S as well as by relatively small wave amplitudes at the corresponding epicentral distances near 100°. The distance of $\Theta = 103°$ where the P waves arrive which touch the core at their deepest point is marked by a rapid decrease in amplitudes with distance. For S waves, this point is reached at a slightly greater distance than for P; the difference results from an increase in Poisson's ratio with depth.

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Letters to the Editor

EXTRAPOLATION OF SCALAR MAGNETIC INTENSITY ALONG A RADIUS FROM THE CENTER OF THE EARTH

An approximate method of extrapolating the scalar magnetic intensity along a radius from the center of the Earth is obtainable through a development similar to that applied in the extrapolation of geomagnetic field components [*Zmuda*, 1957a].

In regions that are outside sources of magnetism, the components of the geomagnetic intensity may be expanded in a series of solid spherical harmonics. In polar coordinates r, θ, and ϕ, with origin at the Earth's center, the respective series are

$$X = \sum_{n=1}^{\infty} \sum_{m=0}^{n} \left(\frac{a}{r}\right)^{n+2} \frac{\partial}{\partial\theta} f_n^m(\theta, \phi) \qquad (1)$$

$$Y = -\sum_{n=1}^{\infty} \sum_{m=0}^{n} \left(\frac{a}{r}\right)^{n+2} \frac{1}{\sin\theta} \frac{\partial}{\partial\phi} f_n^m(\theta, \phi) \qquad (2)$$

$$Z = -\sum_{n=1}^{\infty} \sum_{m=0}^{n} (n+1) \left(\frac{a}{r}\right)^{n+2} f_n^m(\theta, \phi) \qquad (3)$$

where X, Y, and Z, are respectively the northern, eastern, and downward components; a is the radius of the Earth; and f_n^m is a spherical surface harmonic of degree n and order m.

In terms of the field components, the scalar magnetic intensity F may be written as

$$F^2 = X^2 + Y^2 + Z^2 \qquad (4)$$

Squaring each series in (1), (2), and (3), and then substituting in (4), one obtains for the intensity at collinear points

$$F^2 = \sum_{c=0}^{\infty} F_c^2 \left(\frac{a}{r}\right)^c \qquad (5)$$

or

$$F^2 = \sum_{c=0}^{\infty} F_c^2 e^{-2\tau_c h} \qquad (6)$$

where F_c is part of the total intensity observed at $r = a$; e is the base of the natural logarithm; τ_c equals $c/2a$; h is the distance above the surface $r = a$. The variation with altitude in (6) is obtained from that in (5) with the aid of the following relationships

$$\begin{aligned} \left(\frac{a}{r}\right)^c &= \left(\frac{a}{a+h}\right)^c \\ &= \left[\left(1 + \frac{h}{a}\right)^{a/h}\right]^{-ch/a} \\ &\cong e^{-ch/a} \end{aligned} \qquad (7)$$

Under the assumption that the variation with altitude in (6) may be adequately characterized by the use of a single τ, (6) may be written as

$$F^2 = F_0^2 e^{-2\tau h} \qquad (8)$$

or

$$F(h) = F_0 e^{-\tau h} \qquad (9)$$

where F_0 is the total value of F at a point on the surface $h = 0$.

Eq. (9) is similar in form to the expressions applicable to the extrapolation of field components.

With (9), if F is known at two points along a radius, τ may be obtained and then used to compute F at additional, collinear points. When the measurements are made at points that do not lie along a radius from the Earth's center, the exponential formula of (9) is not applicable; but the extrapolation may be effected by means of a Taylor series [*Zmuda*, 1957b].

Studies wherein it may be profitable to use either the exponential formula of (9) or the Taylor series are, for example, analyses of satellite magnetic data or of the total magnetic anomalies treated in geophysical prospecting.

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PARLIAMENT OF SCIENCE, MARCH 15–17, 1958

Under the auspices of the American Association for the Advancement of Science, a Parliament of Science was held in Washington on March 15–17, 1958. The purpose of the conference was to discuss problems of science and public policy affecting the support of science and the improvement of science education. Some 130 participants and approximately 100 observers conferred at the Sheraton-Park Hotel, on the following five major topics: (1) The support of science; (2) The organization and administration of the Nation's scientific effort; (3) Communication among scientists and communication of scientific information; (4) The selection, guidance, and assistance of students for scientific careers; and (5) The betterment of teaching and education generally, as well as in the sciences.

The conferees agreed on several principles: (1) Scientific endeavor is one phase of human intellectual effort, and in order to flourish must be correlated with humanistic efforts; (2) In order to be wisely applied to human welfare, scientists must be free to communicate with each other and with the public; and (3) Scientists are concerned with the finding of new truth, and as citizens they have responsibility to indicate the social consequences of their scientific findings.

As a corollary of these principles, it seemed to be the majority view that we are tending to over emphasize the need for people educated in the physical sciences, mathematics, and engineering. Although men of these kinds are needed, it is also necessary to train more natural and social scientists, and to teach all scientists to be better citizens.

As to the organization of science, the coordinating function of the National Science Foundation was strongly recognized and endorsed. It was judged unnecessary, however, for a separate Department of Science to be set up in the federal government. It was also considered undesirable to have a separate "West Point of Science," in which scientists would be trained under federal auspices.

The following statement is quoted from the Conclusion of the draft report of the Parliament:

"Although this Parliament of Science has quite properly concentrated on problems of science and public policy, and although some of the recommendations are quite specific to science, it must be emphasized in conclusion, as it was in beginning, that science represents only one part of intellectual endeavor. Both public policy and the welfare of science require an educational system that is strong at all levels and in all fields of knowledge. Efforts to advance science at the expense of other fields of learning would harm all fields of learning and the society they serve."

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Report of the Special Committee on the Geophysical and Geological Study of Continents, 1955–1957

G. P. WOOLLARD, *Chairman*

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W. E. BONINI
ROSS GUNN
SIGMUND HAMMER
J. C. HARRISON
J. B. HERSEY
B. F. HOWELL
P. M. HURLEY
M. J. S. INNES
H. R. JOESTING
GORDON LILL
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FRANK PRESS
DONALD RICE
HOWARD TATEL
J. TUZO WILSON
J. LAMAR WORZEL

The advent of the International Geophysical Year and its program of Earth studies is serving to advance a major portion of the program this Committee has been sponsoring over the past twenty years. Many of the members of the Committee are closely identified with the program for the International Geophysical Year, and this overlapping of interests is bound to be reflected in the Committee's activities. The present report will deal principally with studies that have been undertaken by the Committee and its members for a number of years and with activities that are not identified with the IGY effort.

Seismological studies—Among the many important studies now in progress under IGY sponsorship which are a continuation of earlier studies are the seismological studies of crustal structure based on surface explosive blasts. In this field, attention is called to the work of two groups who are working in plateau areas to test the universality of the apparently anomalous results obtained earlier in such regions. In the Andean Plateau of South America the Department of Terrestrial Magnetism of the Carnegie Institution of Washington has been making measurements near Cerro de Pasco, and in the central plateau of Mexico the University of Wisconsin has been making measurements near Durango. Earlier crustal measurements based on explosive blasts carried out in both the Colorado Plateau and the Plateau area of South Africa indicated that the thickness of the crust as defined by the 8 km/sec discontinuity is of the order of 30–35 km.

This is essentially the same value that is found to be characteristic of the continental coastal areas. In view of the well established verification of the hypothesis that crustal thickness and surface elevation are directly related in a manner analogous to that embodied in the Airy theory of isostasy in crossing on to the continents from the ocean basins, the plateau areas of high elevation would be expected to be underlain by a crust approaching 50 km in thickness. That the seismic studies in the plateaus did not confirm this was a distinct surprise, particularly since both of the plateaus studied are characterized by marked regional negative Bouguer gravity anomalies approximating −175 mgal. Verification of the original measurements in the Colorado Plateau area by studies conducted by the University of Utah based on the large blasts fired near Salt Lake City this past year would tend to rule out possible faulty observations as an explanation, as would the very extensive and detailed measurements that were made in South Africa.

Analyses made at the University of Wisconsin of crustal-structure variations based on gravity data, while showing excellent agreement with the results from seismic blast studies as regards the transition in structure in crossing from oceans to the continents, suggest a crustal thickness from 12 to 15 km greater than is indicated by the blast data in continental areas of high elevation. A clue as to the cause of this discrepancy is offered by the recent phase-velocity-dispersion studies of surface waves from distant earthquakes carried out by the Lamont Geological Observatory of Columbia University and the Seismological Laboratory of the California Institute of Technology at Pasadena. These surface-wave studies suggest variations in crustal thickness on the continent that are in substantial agreement with the results based on the analysis of gravity data. This implies that the cause of the discrepancy lies in the surface-blast measurements and that the explanation is probably related to variations in velocity structure within the crustal layer itself that are not being detected by the measurement techniques now being employed.

Seismic results of interest that are being obtained in connection with the IGY glaciological program relate to the thickness of ice in Antarctica. In Marie Byrd Land, a thickness of ice of about 10,000 ft has been found, placing the rock surface at the base of the ice about 5000 ft below sea level. A similar thickness of ice is reported for the South Pole and at several other locations.

While full reports are not available as to the success achieved in recording the subsurface atomic blast fired by the AEC in October, it appears that the blast was recorded with field equipment out to the 20-degree discontinuity in Mexico by the University of Wisconsin team working on crustal structure in that area, and at closer distances in Nevada, Utah, and California by various other groups. It is earnestly to be hoped that the policy of notifying the scientific community in advance as to blast times, and that of releasing information as to the instant of the explosion, will be continued.

Another portion of the IGY program that is of interest is the expanded network of continuous recording seismograph stations established throughout the world. These can be expected to yield much data that will help clarify the present picture of crustal structure beneath the continents and ocean basins as well as the deeper structure within the earth.

From a tectonic standpoint, it is of considerable interest that recent careful analyses of earthquake data show that the predominant movement associated with recent earthquakes has been one involving transverse motion rather than vertical displacement.

Gravity—One of the principal objectives of the U. S. IGY program is the establishment of an international worldwide set of gravity control points that can be used both for integrating the world's gravity data into a unified whole and as a standard for the calibration of relative gravity measuring devices. This work is a continuation of the program that the University of Wisconsin has been conducting over the past few years under the auspices of the Air Force Cambridge Research Center using the compound quartz pendulums developed by the Gulf Research and Development Corporation. The program includes the establishment of four meridional lines of measurements which roughly will follow from Point Barrow, Alaska, down the west coast of South America to Punta Arenas, Chile; from Thule, Greenland, down the east coast of North and South America to Punta Arenas; from Hammerfest Norway, to Capetown, South Africa, and from the Aleutian Islands down the island archipelagoes east of Asia through Australia to Antarctica. To strengthen these measurements, an effort is being made to get observations made with as many other sets of first-order pendulum apparatus as possible, particularly the Cambridge University (England) pendulums which have been used so extensively on earlier measurements throughout the world. This work it is hoped will remove the present ambiguity in international gravity measurements resulting from varying gravity standards being employed. Another phase of the international gravity program, being conducted principally by the University of Wisconsin, is the tightening of the international network of world gravity bases through repeat gravimeter measurements, a program originated under the auspices of ONR.

In the United States, the work of the Committee centers on the preparation of a national gravity anomaly map. This project, which is nearing completion, has been a cooperative venture involving government agencies, universities and the oil industry. The map is to be published by the U. S. Geological Survey and will be a companion map on a scale of 1:2,500,000 to the new geological and tectonic maps of the country that are now in preparation. All observations are being processed with IBM equipment and final data will be available in printed form through the U. S. Coast and Geodetic Survey, which agency has agreed to serve as a national repository. A similar gravity map for Canada is also now in preparation by the Dominion Observatory and is expected to be released this spring.

Of interest from the standpoint of geology and crustal structure is an analysis, now in preparation by the Chairman, of the relation among regional gravity anomalies, geologic structure, and crustal structure as determined from seismic measurements. Results of this study to date suggest that the concept of an elastic crust with sufficient strength to sustain superimposed loads represented by changes in topography, advanced by Gunn, holds for much of the western mountain region. In this area the overall anomaly picture suggests a thick crust averaging about 45 to 48 km in thickness, which is flexed beneath mountains such as the Bighorns and the Uintas. Over the eastern part of the country it appears crustal thickness is much less and varies between 30 and 40 km, with areas of maximum thickness corresponding to areas of structural uplift, and areas of minimum thickness (at least in some localities) corresponding to areas of surface subsidence. This last would imply a situation analogous to steel in tension that has been stretched beyond the yield point. As a test of the above, the University of Wisconsin plans to make seismic explosive-blast studies in selected areas to ascertain if there is corroborative evidence.

Magnetism—It is particularly gratifying to note that the country is being gradually covered more and more by aeromagnetic surveys and that the areas of detailed surveys are being interconnected by traverses flown purely out of scientific curiosity. It also is gratifying to note the success with which aeromagnetic data are being applied in determining the depth of the basement in sedimentary rock areas that are uncomplicated by the inclusion of volcanic horizons. For many areas such as the Coastal Plain regions, the magnetic values appear to offer an economical technique for estimating basement depth with sufficient accuracy for many geologic studies that otherwise would have to wait many years if seismic or drill hole data were to be the only source of information. The present program of the U. S. Geological Survey for working up the large number of cross-country profiles they have taken, as well as the policy of commercial organizations to take such measurements and publish them, can be expected to yield some most interesting and enlightening data concerning near-surface structure.

A map that would be of interest to many geologists is an unpublished one compiled by the U. S. Coast and Geodetic Survey showing the areas of anomalous magnetic declination which must be considered in preparing the smoothed declination charts that are published regularly. The publication of this map would give much valuable information that would aid in both the study of regional geology and also in the correct interpretation of variations in regional gravity anomalies.

Basement study—Through the Committee Chairman, the Committee is cooperating with the Basement Study Committee of the American Association of Petroleum Geologists in compiling all well data involving the basement complex throughout the country. This material is being used to establish a file showing the location of basement wells, depth to basement, type of rock, location of cores, etc. Through the cooperation of the Society of Exploration Geophysicists as well as of this Committee, geophysical data bearing on the basement are also being compiled, so that a fairly complete basement configuration map can be prepared. The last map of this type available for the country as a whole was the one prepared by the Committee in 1939 under the direction of W. T. Thom, Jr., Chairman of the Committee at the time. Since then many new data have become available, and the AAPG Research Committee is to be commended for underwriting this study.

Advancement of geophysics in colleges and universities—As much of the geophysical equipment given to schools either never comes into use or falls into indifferent custody in the course of faculty changes, the Chairman of the Committee proposed to the Geophysical Domain Committee of the American Petroleum Institute that a central respository be set up for lending equipment on a temporary basis to schools having students actively interested in working with such equipment. While no formal program has been established as yet for financing the maintenance of equipment, or for training people in the use of it, for reducing the data, etc., the Committee, through its members, was instrumental during this past year in getting geophysical studies started on regional geological problems on a *pro tem* basis at four institutions. This policy should pay large scientific dividends for the small outlay in funds and time required.

Astronomical studies of interest—The recent work of Gerard Kuiper of Yerkes Observatory concerning the Moon, its surface features and their origin will be of interest to all students of the Earth. As there has been some apparent misunderstanding of his position concerning possible analogies between Earth structure and that on the Moon, Kuiper, at the request of the Chairman, kindly consented to write a short abstract on his findings and views, which is attached.

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APPENDIX

A REPORT ON RECENT LUNAR STUDIES AND THEIR BEARING ON THE NATURE OF TERRESTRIAL CONTINENTS AND OCEAN BASINS

G. P. Kuiper

The common distinction between the low dark maria and high brighter continents, readily made on lunar photographs, must be refined. The bright areas are of two types: (1) accreted crust, modified by a sequence of impacts that led to the formation of the familiar large lunar craters; and (2) maria or accreted crust, buried by material clearly ejected from Mare Imbrium and a few smaller splash centers. The major mountain ranges (Alps, Caucasus, Apennines, Carpathians) belong in this second category; they seem to be composed of light-colored blocks of crust, mixed with large quantities of darker lava, now solidified, which look somewhat like mud flows.

The recent suggestion by T. Gold and others that the maria are featureless because they are filled with a very deep layer of dust is contradicted by several groups of observations: (1) The maria, seen under very low Sun, show an intricate fine structure, including discrete flows, minor faults, graben, etc. (2) Impact craters situated on the 'shore' lines of maria are often tipped toward the mare, like partly-sunk boats lying against the shore line of a lake. Apparently, the foundations of these crater ruins were melted locally and the ruins have subsided or even submerged. (3) A compelling argument is derived in the next paragraph from the nature of the ridges on the maria. (4) There is no trace of a filling effect of very small craters such as a thick, mobile dust layer would cause. Actually, the maria are beset with hundred of small craters (about 1 km in diameter and smaller), whose numbers and shapes indicate that they are meteoritic in origin. Large craters, (10 to 100 km), as found on the continents, are nearly absent on the maria. These large craters appear to represent an early phase of lunar development, preceding the development of the maria and partly concurrent with it. The maria were probably formed about 4.5 billion years ago.

The maria are of two types: (a) Nearly circular basins, surrounded by mountain rings, that appear to have been caused by very large impacts; they are essentially giant lunar craters; and (b) areas clearly inundated by lava. Intricate systems of low, long ridges occur on all maria, apparently the result of lateral compression which is attributed to cooling and shrinking of the underlying shells. My recent studies have shown that for roughly one-third of their length these ridges have no visible fine structure; another one-third can be seen to have cracks of widths up to several hundred meters running roughly along the crests of the ridges, while the remainder show dikes, usually as continuations of the cracks. The dikes barely protrude above the ridges, and can be seen by their somewhat lighter color and the shadows they cast at very low Sun. The general outline of these ridges is often nearly concentric with the 'shore' lines of the maria, but their detailed structure frequently resembles a twisted rope, that is, with a tendency for an echelon structure. As a result, the individual elements (usually a few km long) are often inclined some 45° with respect to the inferred lines of compression; this is quite understandable dynamically. The ridges and their dike systems are among the most powerful arguments for the view that the maria resulted from melting and subsequent solidification, and are not basins filled with electrically charged mobile dust particles. In principle, the ridges will determine the depths of the maria basins. The curious ridge systems in Mare Nubium and Mare Tranquilitatis show unmistakably the shallowness of these maria and the presence of older bottom topography. Some 15 beautifully shaped volcanos are found in three regions, on shallow maria. These volcanoes are all about 7 to 8 km in diameter measured at the base, and have outer slopes of about 5°, comparable to the slopes of basaltic volcanoes on Hawaii; while all but one show central calderas. In the same regions many smaller volcanoes are present as well.

On the continents no such volcanoes have yet been found, but there are many isolated and rather shapeless 'humps,' each a few km in diameter; examples are found between the craters Schiller and Schickard. These humps have sometimes been regarded as distant splashes from Mare Imbrium; but my recent observations have shown the presence of dikes on these masses, sometimes as many as four. This appears to establish that they are not foreign additions, but probably local extrusions.

The lunar maria differ from the terrestrial ocean basins in that the crust of the maria appears to be of limited depth, as judged by the ridge systems, except perhaps for the central zone of Mare Imbrium (the impact center) where no ridges are present at all. One surmises that the outer layers of the Earth melted much more completely than those of the moon, some 4.6 billion years ago. Two causes for this difference are apparent: (1) the greater heat at the surface of the Earth resulting from convection in the liquid mantle, and (2) the presence of an atmosphere on the Earth, which at that time may have been a much more efficient insulator than at present, owing to the presumably very large water-vapor content prevailing at the high temperatures.

The lunar maria differ further in that they show no clear evidence of lava flows that are substantially younger than the maria themselves. This is indicated by the ray craters which have scattered their white material (probably rock flour) everywhere over the maria; since these craters are as large as the pre-mare craters and much larger than the contemporary meteor craters, of which the maria have their expected share, the ray craters are probably early post-mare in age. (It is very probable that the large craters on the Moon are due not to asteroidal meteorites, but to a ring of small satellites moving around the Earth, which the Moon slowly transgressed in its recession from the Earth due to tidal friction some 10^9 years after its formation, that is, some 4.5 billion years ago). On the other hand, evidence for more recent lava flows does exist in smaller areas, such as eight small regions in the crater Alphonsus.

The lunar continents differ from the terrestrial continents in that the latter appear to be the result of a fractionation process that caused the composition to be no longer representative of the silicate mixture found in meteorites (which presumably resembles that of the bulk of the Earth's mantle). The lunar continents seem to be the old accreted crust, reworked locally by impacts, but in composition presumably similar to the average of the meteorites. This difference, like that between the lunar maria and the terrestrial ocean basins, may be due to the difference in surface temperature of the two planets at the time of maximum melting.

A new photographic lunar atlas is now in preparation based on the best plates available at different observatories.

Yerkes Observatory, University of Chicago, Williams Bay, Wisconsin (*G. P. K.*).

Discussion of "The Effect of Non-Representative Sampling on Linear Regressions as Applied to Runoff"

BY W. D. POTTER

[*Trans.*, **38**, 333-340, 1957]

N. J. Cochrane (Alliance House, Caxton Street, Westminster, London, S.W. 1, England; received August 12, 1957)—Potter's analysis of the effect of non-representative sampling is salutary but a further complexity may lie in the applicability of extreme-value statistical theory to hydrological problems. Some recent investigations by the writer and others suggest that the prognostications of a Gumbel-type flood analysis can be grossly in error even when the period of the record is several decades. Perhaps the reason is that hydrological events are not all of a random nature. They certainly are not random but demonstrably cyclic in the cases of the Lake Nyasa-River Shire and Lake Victoria-River Nile complexes in Africa, and also in the cases of the Rivers Thames and Severn in England.

J. L. McGuinness and *D. L. Brakensiek* (U. S. Agricultural Research Service, Coshocton, Ohio; received August 28, 1957)—The author is to be commended for bringing to the attention of hydrologists the dangers inherent in the extrapolation of recorded runoff data to other watershed sizes and into other localities. The scarcity of suitable records in most areas of the country, especially reliable records in the smaller size classes, has made this practice rather prevalent. Extrapolations of hydrologic data must always be made as a matter of course but on the basis of the author's study it is apparent that considerable care must be taken to insure reliable results.

In addition to area and location representativeness, one must also consider the representativeness of precipitation factors. This is especially pertinent as the author's P and S ratios and Q values were defined from a probability study of a short period (1938-1948) of record. In other words, for a frequency analysis of a short set of data to have meaning, it must be shown that the years of record are representative of the long-time weather pattern. The author is evidently aware of the need for a representative precipitation sample since in the description of the original study in 1953, he deals at some length with the computation of long-term P and S ratios. At least one other of the author's previous works dealt primarily with this subject [*Potter*, 1949].

As in this paper the period of study is not shown to be of a typical weather pattern, the writers suggest the U-test [*Mann* and *Whitney*, 1947] as a simple, objective method of checking representativeness. For this test, records from a long-term weather station would be used. The following example uses the 60-minute maximum intensities per year for Columbus, Ohio, for the period 1899-1951. The U-test is used to determine whether the frequency distribution of the period 1938-48 is identical with that of the longer period of rainfall record. If it is the same, then the author's conclusions are based on a weather sample which is representative of a much longer period at that location.

First the 53-year record of 60-minute maximum rainfall values at Columbus were ranked in decreasing order. The sum of the rank numbers T was found to be 186 for the 1938-48 period. If the number of years in the 1938-48 period is denoted as $m = 11$, and the remaining years as $n = 42$, then the statistic, U, may be computed as

$$U = mn + [m(m + 1)/2] - T \tag{1}$$

When the hypothesis of the two distributions being identical is true, (for m and n both larger than 8) the random variable U will have approximately a normal distribution with the mean

$$E(U) = mn/2 \tag{2}$$

and variance

$$\sigma_U^2 = mn(n + m + 1)/12 \tag{3}$$

For the Columbus data, $E(U) = 231, \sigma_U = 45.6$, and

$$t = U - E(U)/\sigma_U = 2.43 \tag{4}$$

The probability of a value of t greater than ±2.43 is approximately 1.5 pct. The conclusion would be drawn that the 1938-1948 sample has a different frequency function than the remaining period and therefore the sample period can not be considered a representative period at Columbus, Ohio with respect to maximum 60-minute intensities.

Data were not available to the writers for investigating the representativeness in time of *P* and *S* ratios and *Q* values at other locations.

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Manuel A. Benson (U. S. Geological Survey, Washington 25, D. C.; received September 4, 1957)—There are some rather vague conceptions used in this article which seem to need some further thought and clarification. For example, "... the Allegheny-Cumberland Plateau, an area considered to be homogeneous as to physiographic characteristics, ..." The term 'homogeneous' is never defined hydrologically, yet this is vital to the discussion. The *T* factor for each station (in Table 1) shows a considerable range, indicating large differences in slope for the individual drainage basins. The region could not therefore be considered homogeneous with regard to the physiographic characteristic of slope. As shown by the variation in *P* and *S* indices (Table 1) both the rainfall intensity and rainfall storm frequencies show significant variation within this region. Is this region homogeneous with regard to the physiographic characteristics of rainfall? Again, if a region is homogeneous, should it make any difference in which part of the area any particular station is located? Yet, the definition of 'representativeness' is based on sampling with respect to location. It appears to the writer that if the need for representative sampling with respect to location is proved, that constitutes a direct proof of non-homogeneity.

The concept of representativeness as set up here is in general somewhat questionable. The data to be analyzed consist of one dependent variable (the ten-year flood), and four independent variables, namely, the area, the *T*, *P*, and *S* factors. Sampling over the range of drainage area is defined as a measure of representativeness, yet why is it not equally valid to require sampling over the range of the *T*, *P*, and *S* factors? Proper sampling should adequately represent the basic distribution of all variables.

Results of the comparisons of non-representative samples with the entire group or the test sample might be interpreted as follows:

(1) Samples unbalanced as to location lead to regression curves departing from the test curve because of the nonhomogeneity of the region. (If Zones 1, 2, and 3 differ in general characteristics the elimination of data from any one would necessarily give a relation departing from the overall average.)

(2) Samples unbalanced as to size represent arrays in which the range in one of the variables has been reduced. This is obviously true in the case of samples 6 and 7, and effectively true in the case of sample 5. Reduction of the range in one of the variables would be expected to decrease the precision of definition of the regression line.

Statistical methods developed over a long period of years have resulted in an almost universally used measure of the error of estimate in correlation studies. This is the 'standard error.' It includes a correction for the number of lost degrees of freedom associated with the number of variables considered and a correction for the number of items in the sample. The method used here, which computes percentage errors, neglects entirely both of these vital considerations. The computed percentage error for any sample does show results for that sample but is not a measure of the error of prediction. The author states "... they (the distribution-of-error curves) were used as a yardstick to measure the relative accuracy of prediction that might be expected from a general application of each of the regression equations." If a straight line were to be fitted by least squares through three points, a small percentage error might be computed at 67 pct of the sample size. Yet that figure would be useless for prediction purposes, since the standard error of prediction based on three points would most likely be extremely high. Percentage errors for samples of different size, as computed by the author, are not even a relative measure of the accuracy of prediction. Conclusions involving the size of samples are patently inappropriate when based on procedures which neglect the sample size.

There is a need for sampling in making hydrologic analyses, because the vagaries of establishing data-collecting stations frequently produce unbalanced coverage in location, size of area sampled, and other factors. However, sampling must be judicious because there is frequently all too little hydrologic data available. Another alternative is to use all the records but to weight them so as to remove the bias caused by imbalance. This has the advantage that use is made of all the data available.

W. D. Potter (Bureau of Public Roads, Washington, D. C.; Author's Closure)—Cochrane's observations regarding the possible cyclic nature of hydrologic events are undoubtedly true in, at least, some instances. Unfortunately, the meagerness of available data precludes a determination of whether or not this cyclic nature pertains to all such data or is limited only to isolated cases.

The U-test, described by McGuinness and Brakensiek, should prove to be a very useful tool for hydrologists. As pointed out in their comments, the values of P and S, computed for the short period of runoff record, are only used to establish the relation between the ten-year peaks and the rainfall that was their source. To use the original regression equation to estimate a ten-year Q from an ungaged watershed, new values of P and S, based on long-term records, must be used. These values were computed for the Allegheny-Cumberland Plateau and presented as a map showing lines of equal P and S ratios in a later publication [*Potter*, 1954].

Aside from a doubtful admission that sampling might be necessary for some hydrologic analyses, Benson seems to question practically the entire paper.

His first question revolves around what is meant by homogeneous and the degree of homogeneity ascribed to the Allegheny-Cumberland Plateau. Webster defines homogeneous as being, "of the same kind or nature" (not identical) "consisting of similar" (not the same) "parts or elements." Certainly the geology of the watersheds is similar, the Plateau being an eroded peneplain underlain by nearly horizontal strata of sandstone, limestone, and shale. The side slopes are similar since the valleys are all steep sided and V-shaped. The watersheds are also similar in that their soils are shallow and their drainage pattern typically dendritic.

The fact that these physiographic characteristics are similar does not signify that they are identical or that possible differences might not exist between various portions of the area. These differences would have been greater, however, if the comparisons had been between watersheds where physiographic characteristics were dissimilar and it is for this reason that they were limited to one homogeneous area.

It is true that there is a considerable range in the values of T, but this would be true even within the confines of a single watershed since the slope of the stream channels is steeper near the headwater than in the lower reaches. It is also true that there is a considerable range in the rainfall indices P and S, but these can more properly be classed as meteorologic rather than physiographic characteristics.

Benson states that a sample is nonrepresentative when balanced only with respect to location and watershed size without regard to all of the independent variables. I have no fault to find with this statement except that it implies that these requirements were not met in the selection of the representative samples used in the paper. Since, however, the independent variables T, P, and S are very closely correlated with either location, watershed area, or both, it is evident that any sample balanced in these respects is also balanced with respect to those variables.

Benson's third question concerns the use of the standard error as a measure of the error of prediction.

When a random sample is drawn, it is seldom that any assurance can be had as to whether or not it is representative of the population from which it is drawn. The larger the sample the greater the chance that representativeness will be obtained. Likewise, the greater the number of variables involved, the smaller the chance that the sample will be representative. In such cases the standard error, with its built-in corrections for sample size and number of variables, gives the most reliable estimate of the precision that may be expected from predictions based on sample relationships.

If, however, the sample is carefully selected so as to be truly representative of the population from which it is drawn, then the distribution of the sample and population should be the same. Adding to the size of such a sample would not increase its representativeness, since it was already representative. Likewise, the number of variables involved would not affect its representativeness if the entire range of these variables had been sampled.

The above statements are substantiated by the fact that when the 34-watershed test sample was applied to the original regression and to regressions I, II, and III, the distribution of error graphs derived from the average of regressions I, II, and III were practically identical with that derived from the original regression. This was true in spite of the fact that regressions I, II, and III were derived from samples of only 18 watersheds while the original was derived from 51. The computed upper and lower limits of the standard error for the average of regressions I, II, and III was 30 and 23 pct respectively, or an average of 26 pct, while that for the original regression was only 18 pct. If these standard errors had been measures of the precision to be expected, then the distribution-of-error graph for the original regression should have shown a substantially smaller error than that for regressions I, II, and III for all values of per cent of sample. Since, however, all four regressions were based on representative samples, the precision of their estimates was found to be the same.

If relations are established from a sample drawn from selected zones or size groups, then the standard error would be a measure of the accuracy of prediction only for that portion of the population included in those same zones or size groups. Where the relations are based on representative samples, however, the accuracy of prediction remains constant for all portions of the population. For example, regression VI was derived from a sample of 16 watersheds from Zone 3. The computed standard error was 16 pct (average of upper and lower limits). When applied to a sample drawn from Zone 1, however, the error for 68 pct of sample was found to be 34 pct. Likewise, the computed standard error for regression VIII (based on a sample from size group C) was 20 pct. When applied to a sample drawn from size group A, the error for 68 pct of sample was found to be 57 pct. On the other hand, the error for 68 pct of sample for the average of representative regressions I, II, and III was found to vary by no more than three per cent regardless from which zone or size group the sample was drawn.

Finally, Benson suggests that the use of all records would be more advantageous than selective sampling but that such a procedure would necessitate weighting the data to prevent bias due to imbalance. Since the relative merits of these two methods is outside the scope of the paper, I will merely point out that the difficulty with Benson's suggestion lies in a selection of weights that would insure against intuitive selection.

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Reviews, Abstracts, and Bibliography

Reviews and Abstracts

A. HUNTER DUPREE, *Science in the Federal Government—A History of Policies and Activities to 1940*, Belknap Press, Harvard Univ. Press, Cambridge, Mass., 460 pp., 1957, $7.50.

The basic question to which Dupree addresses himself is: By what processes have science and Government developed their mutual responsibilities to each other? His approach to the problem is through a series of interrelated essays on the histories of many agencies, and comments on the reasons for their success or failure in attempting to establish a part of the Federal policy relating to scientific matters. Throughout the book are incidents to support the point that science has meant different things to successive generations, and at any one time it has meant different things to a wide variety of groups. It is the interplay among these various concepts that provides the full historical definition of science. Because the emphasis is on the institutional setting, Dupree's use of the term science includes education, communication, and organization, as well as the creation of new knowledge by research. As such, this is a story both of institutions and of ideas.

Through the patent clause of the Constitution and congressional power over coinage, weights, and measures, science has been in the Government since the beginning in 1789. The following century and a half can be divided rather arbitrarily into four periods of the gradual emergence of science as a function of Government. The earliest is the pre-Civil War period, in which the first six chapters tell the story of Thomas Jefferson's and John Quincy Adams' enlightened attempts to use science for the benefit of mankind; the establishment of the Smithsonian Institution when Congress reluctantly accepted as a gift the estate of the Englishman who never visited this country; the dominance of the Coast and Geodetic Survey; the early exploration and surveys of the West. It was in the succeeding major period, from the end of the Civil War to about 1890, that research expanded in Agriculture, facilitated primarily by the Morrill and Hatch Acts permitting grants-in-aid to land-grant colleges. The event during this period that changed the role of science in Government probably more than any other single factor was the consolidation of the western surveys that resulted in the appearance of John Wesley Powell as a new type of bureau chief.

The conservation movement led by Gifford Pinchot and Theodore Roosevelt dominated the period between 1890 and the World War I and led to the creation of the Reclamation Service, Bureau of Mines, Public Health Service, National Park Service, and Forest Service. World War I provided for the development of relationships between industry and Federal science that have been further strengthened continuously to the present. In the years after the War the role of social sciences expanded through such agencies as the Bureau of Agricultural Economics, the Bureau of Home Economics, and the Tennessee Valley Authority. As Dupree points out, through all the twists and turns of the political history of the United States the policies and activities of the Government in science make a single strand which connects the Constitutional Convention with the National Science Foundation.

Despite the abundance of detailed information and the scholarly documentation of primary sources, this book is not simply a who-did-what sort of historical treatment. Dupree's penetrating insight and analytic interpretation of the events show the logical reasons for developments that have heretofore been obscure. The kind of thought-provoking contribution that he has made to the history of science throughout the book is exemplified by the chapter on the Civil War relating to the genesis of the National Academy of Science. (Essentially the same treatment appears in *The Founding of the National Academy of Sciences—A Reinterpretation* by A. Hunter Dupree in Proc. Amer. Phil. Society vol. 101, No. 5 Oct. 1957.) The usual way of describing the origin of the National Academy is to say that it was created by President Lincoln in 1863 to assist the Government in the Civil War. Dupree's examination leads to the conclusion that the Civil War was merely the occasion and not the cause of the birth of the Academy. The lines of organization had been formulated as early as 1851, and a closely knit group of scientists of the highest prestige worked toward a National Academy from that time onward. When they had succeeded in 1863, their attempt to enter the field of weapons research was almost a complete failure, and it was their losing control of the organization after the War that finally enabled it to survive.

Dupree treats profoundly many topics that have concerned scientific administrators throughout history. For instance, in discussing the development of a scientific program in the Department of Agriculture, he points out that the Department achieved success only after it abandoned the discipline-type organization in favor of a problem-type organization. That is, the problems of growing particular crops or improving animals became the central interest instead of the program centering around chemists who tested various substances, and the Bureau mobilized teams of experts from various disciplines to work on each problem.

Although John Wesley Powell has been one of the most intensively studied figures in American science (T. G. Manning's forthcoming history of the Geological Survey will make the coverage still more complete), Dupree adds an interpretation to his achievements which has not been pointed out so clearly by previous biographers. Following the ideas expressed concerning the development of science in the Department of Agriculture, Dupree recognizes Powell as the personification of a new type of bureau chief able to develop the Geological Survey into an ideal bureau within a short period of time. Some of the criteria of an ideal bureau, as exemplified by these two agencies, are control of flexibility through lump-sum appropriation so that emphasis can be shifted as the problems change in anticipation of need; development of a stable corps of scientific personnel who are competent, loyal, and confident that their work is important to the country; establishment of harmonious relationships with groups such as Congress, other agencies, the American Association for the Advancement of Science, and universities. The conclusions are that science became more effective when its objective was research on specific broad problems by a stable organization centered around the problem rather than the disciplines.

Dupree, formerly at Harvard and now with the University of California, has provided us the most complete and understandable history to 1940 of science in the Federal Government, which deserves thoughtful study by all who are concerned with the force of science and Government in our society; moreover, the 54 pages of bibliography and annotated footnotes make this a most useful reference book on the subject.

William Back

Lettau, Heinz H., and Ben Davidson (ed.) *Exploring the Atmosphere's First Mile*: Proceedings of the Great Plains Turbulence Field Program, 1 August to 8 September 1953, O'Neill, Nebraska; vol. 1, Instrumentation and Data Evaluation; vol. 2, Site Description and Data Tabulation, Pergamon Press, 578 pp., 1957, $20.00 (2 vols.).

These volumes present both the composite panoramic picture and small-scale views of an effort which was unquestionably the most elaborate series of micrometeorological observations ever made. According to the explanatory note introducing volume 1, "The project was conceived and organized by the Geophysics Research Directorate with the primary objective to study the profiles of wind, temperature, and other meteorological quantities in the lower 2000 m (atmospheric boundary layer); the turbulence structure; boundary fluxes of energy, momentum, and moisture; and the physical soil properties affected by diurnal variations of meteorological elements." The site at O'Neill, Nebraska, was chosen in order to approximate closely an ideal micrometeorological site of flat, uniform terrain.

Altogether, 15 universities, scientific institutions, and government services participated cooperatively in the project with logistical support provided by the Air Force. This effort thus represented the pooling of resources of the large majority of the groups undertaking major research in the field of micrometeorology in the United States at that time.

Following the introduction by the editors, which includes their over-all impressions of the program, volume 1 is divided into 7 chapters which discuss in order, the synoptic material, subsoil measurements (including heat transfer at the ground-air interface), interface measurements, mast profile data of 'meaned' quantities, fluctuation quantities, and free air observations. The final chapter is called an appendix and serves as rather a digest of the observational results and includes partial evaluations, largely in terms of derived quantities. Each chapter on instrumentation is divided into a number of sections dealing with the measurement of a particular quantity, for example, soil temperature, or closely related quantities such as radiation measurements. Each individual section begins with a relatively short introductory article by an expert in the particular field setting forth the general significance of the quantity in the total picture and the problems involved in its measurement. Individual scientific articles then follow in which details of the appropriate measurements made by a group are presented by a member or members of that group. These comprise a total of some 59 papers by over one half as many different authors. As might be expected, the relative detail of presentation and error analysis is not uniform among the several papers. For one thing, details of some of the instrumentations had been previously published, and others have been presented separately in the form of Project Reports subsequent to the execution of the Great Plains Program. However, the references seem to be adequate for one wishing to delve deeper into any one of the subjects. In passing it might be of interest to note that several relatively novel instrumentations were on field trial in the program, particularly for the study of wind fluctuations, and the discussions of the findings are sometimes expressed with refreshing candor.

The final chapter of volume 1, the Appendix, will of course be of greater general interest, especially to readers who are not interested in or concerned with the mechanics (and electronics) of measurement. Three sections, all by H. H. Lettau, represent the essence of the integrated immediate returns of the elaborate program. They are, following the numbering system of the volume: 7.3, Computation of heat budget constituents of the earth-air interface; 7.4, Computation of Richardson numbers, classification of wind profiles, and determination of roughness parameters; and 7.5, Summary of non-dimensional characteristics of boundary layer theory.

The material and analyses are not presented in these sections at a particularly elementary level. Therefore, some of the arguments and developments will not be easy to follow without some background knowledge in the specialized field of micrometeorology. Questions or even points of difference of detail with Lettau's interpretations and computations are to be anticipated even among micrometeorologists. For example, this reviewer is skeptical of the validity of the 'inertial subrange' parameters computed and presented in Table 7.5.14 (p. 370). Only a necessary, and not sufficient condition was found (the power-spectral density of turbulent vertical motions varied as the $-\frac{5}{3}$ power of frequency) to show that an inertial subrange did exist in the observed frequency range. This fact is not pointed out in the discussion.

Volume 2 contains two chapters, the General introduction, and Data presentation, and closes with an author index. The introduction has four sections devoted to a general description of the site (including a map of the lay-out of observation sites, topographic maps of the immediate and general regions, and aerial and eye-level photographs), the climatology of the region, and the particular conditions during the late summer of 1953. Also included is a section on the scheduling of observations and giving a summary of the data presentation as well as convenient tables summarizing the measurements and data available. The chapter of data presentation, comprising the bulk of volume 2, gives the bi-hourly tabulation of data and synoptic charts for each of the seven general observation periods which average 25 hr in duration. It is pointed out that it was impossible to publish all of the data obtained but "... a certain amount of raw data is preserved on punch cards at the Atmospheric Analysis Laboratory of the Geophysics Research Directorate ... (and) ... can be made available on request."

It is evident that, in total, the task of reducing the large volume of raw data to tabular form was a considerable undertaking. The editors are to be congratulated for their skillful organization of the material in the two volumes which will add greatly to the practical utility of the work, both as reference material and as a data source. The numbering system of the articles in volume 1 and the data tabulations in volume 2 is particularly good. It was chosen so that the first number and the first decimal indicate the same meteorological quantity in both volumes. For instance, articles dealing with temperature profile instrumentation in volume 1 are numbered 4.2.1, 4.2.2, etc., while the tables in volume 2 giving the profile temperatures in each of the observation periods are numbered 4.2.

The quality of the paper and printing are excellent, no typographical errors were noted and the diagrammatic illustrations are adequate. One discrepancy was found, although there might be others, in that Tables 4.2 of volume 2 do not give the MIT 60-min mean temperatures as stated on page 175, and implied again on page 330 of volume 1. Some minor errors were also noted. The computation of R_i for 04h 35m September 8, 1953, 8-m level, 15-min mean in Table 7.4.2 of volume 1 seems to be in error. Also in Table 5.2.a, page 447 of volume 2 the stress at 22h 35m August 18 at the 3-m level has apparently been given the wrong sign as uw is negative. Another point, which is at least annoying, is that the sign convention relative to the direction of the net radiation flux is not consistent in Tables 3.1 and 7.3 of volume 2.

These volumes are not expected to gain a place on the reference shelves of every meteorologist's personal library. The relatively high price of the work will be one deterrent, but more importantly, the subject matter is (unfortunately?) of considerable interest only to a rather limited audience. As previously implied, its greatest value is two-fold. First, as a reference work for those engaged in, or contemplating micrometeorological measurements as few modern techniques were not tried by one group or another. Second, as a source of data obtained at a nearly ideal micrometeorological site. We can expect comparisons with analyses made of the O'Neill data to appear often in micrometeorological literature for many years to come.

The editors and individual authors have done a commendable job of presenting the facts of the Great Plains Turbulence Field Program. Whether the Program accomplished all of its avowed objectives is not within the scope of this review.

ROBERT A. MCCORMICK

Reviews, Abstracts, and Bibliography

Reviews and Abstracts

Abstracts of the papers presented at the Thirty-Ninth Annual Meeting, Washington, D. C., May 5–8, 1958 listed in the order of the last name of the first author

BERNICE ACKERMAN (Department of Meteorology, University of Chicago, Chicago, Ill.) *Liquid Water Contents of Tropical Cumuli*—Continuous measurements of liquid-water content made during the 1956 flight operations of the National Hurricane Research Project have been used to determine the magnitude of cloud water and its distribution in tropical cumuli. Cloud water is found to be unevenly distributed in a horizontal plane through the cloud. The location of the area of greatest water concentration appears to be related to the external wind field. Many clouds are found to have regions in which the liquid-water content exceeds the theoretical value computed for moist adiabatic ascent with no water loss. However, the average liquid-water content for a cloud penetration is always less than the theoretical. The data show that the magnitude of the liquid-water content is correlated to cloud dimensions and to vertical displacement from cloud base.

G. N. ALEXANDER (U. S. Geological Survey, Washington 25, D. C.) *Statistical Implications of the Station-Year Problem*—Very few professional statisticians work directly in the field of hydrology. Consequently concepts such as station-year and plotting-position have to be transplanted into statistical language before the statistical model can be constructed. The station-year problem is here conceived as the appropriate method of combining hydrologic records in a space-time field. The limitations due to spatial correlation have been recognized and discussed, and the advantages of combining records to obtain regional values are appreciated, but the procedures are largely empirical. This paper examines some of the statistical and hydrologic problems involved in constructing a rational model.

PAUL A. ALLEE AND B. B. PHILLIPS (Office of Physical Research, U. S. Weather Bureau, Washington, D.C.) *Measured Values of Droplet Charge, Polar Conductivities, and Potential Gradients in Supercooled Orographic Cumuliform Clouds*—The size of and free electric charge carried by the cloud particles in a supercooled orographic cumuliform type cloud have been measured on a mountain top at an altitude of 6600 ft. The charges observed lead to a droplet charge distribution which approaches that of equilibrium predicted by the theory of random ionic diffusion electrification of cloud particles. Simultaneously, the positive and negative conductivities in the cloud and the vertical atmospheric potential gradient at the site were recorded.

R. A. Allen (Office of Meteorological Research, U. S. Weather Bureau, Washington, D.C.) *A Note on Long-Range Prediction*—Long-range prediction is essentially a statistical process, hence it should be applicable to prediction for an individual day just as to prediction of the mean over a longer period. An experimental method has been developed for making a probability forecast of the maximum temperature for July 4, with the initial prediction made at any time prior to May 31 and revised at intervals from May 31 up to July 3. The risk interval in which the forecast might be useful is shown.

Don L. Anderson and W. F. Weeks (Air Force Cambridge Research Center, Bedford, Mass.) *A Theoretical Analysis of Sea-Ice Strength*—A sea-ice model can be constructed from photographs and the phase curve of sea ice. From this model a theoretical strength of sea ice can be calculated using grain boundary and stress concentration considerations. The strength can be shown to depend strongly on temperature and salinity. Density is a controlling factor in very young and very old ice. The theoretical results compare well with experimental results.

H. W. Anderson (U. S. Forest Service, California Forest and Range Experiment Station, P. O. Box 245, Berkeley 1, Calif.), and **R. L. Hobba** (U. S. Forest Service, Washington 25, D.C.) *Forest and Floods in the Northwest*—Floods result from many factors. The basic factors are the meteorological events that precede the flood and the physiographic and geologic characteristics of the watershed. Varying combinations of these factors bring about wide fluctuations in flood runoff. In the watersheds of the Pacific Northwest, where forest land makes up a large per cent of the total watershed area, it was hypothesized that differences in forest condition alone also cause detectable differences in flood runoff. Using methods of multiple regression, covariance, and double-mass analysis, the differences became apparent and measurable when the variations in flood runoff attributable to the other factors were measured and isolated. Forest conditions were expressed as area logged, age and stocking of the stand, and area denuded. The effects on flood runoff were evaluated for three areas of the Pacific Northwest.

J. K. Angell (Office of Meteorological Research, U. S. Weather Bureau, Washington, D.C.) *An Analysis of Routine 300-mb Transosonde Flights from Japan*—Navy sponsored constant level balloon (transosonde) flights launched from Japan on a routine basis during the fall of 1957 and the winter of 1958 are discussed. Individual transosonde trajectories are shown by month, as well as the mean trajectory for each month. The transosonde data and conventional upper-air data are compared and reference made to the use of transosonde data in weather analysis. Flights of particular interest are studied in detail. Statistics of the wind velocities, accelerations, etc., derived from the trajectories are presented.

Carl I. Aslakson (Aero Service Corp., 210 East Courtland St., Philadelphia 20, Pa.) *Geodetic Control in Jungle Areas*—Oil companies are frequently faced with the problem of delineating oil concession boundaries in unmapped areas. Such boundaries are often defined by latitude and longitude lines drawn on outline maps. Usually, time limits are set for defining the concession boundaries which preclude the use of conventional surveying techniques. This paper describes the manner in which Aero Service Corporation employed shoran trilateration and shoran controlled photography for geodetic control in the Peten area of northern Guatemala. This method is commonly known as the SCP or secondary control point method.

David Atlas (Aerosol Physics Laboratory, Geophysics Research Directorate, Bedford, Mass.) *New Evidence of Meteorological 'Angel' Echoes*—New observations of a variety of 'angel' echo phenomena were made during 1957. These may be grouped into four types: (1) echoes from thermal columns below cumulus clouds; (2) mantle-shaped echoes associated with the boundaries of cumulus clouds; (3) layer echoes associated with sharp vertical gradients or minima in moisture aloft; and (4) anomalous low-level echoes believed to be produced by the boundary surfaces between differentially moistened surface air over adjacent cold and warm water. Characteristics of these various angel types will be discussed along with evidence supporting their interpretation. These observations, and those previously reported of sea-breeze angels, constitute impressive empirical proof of the association between angel echoes and meteorologically induced gradients in refractive index. However, it is still not possible to account for the observed angel cross-sections theoretically using 'reasonable' gradients of refractive index. The regular observation of elevated blobby angel layers indicates that conditions are frequently suitable for enhanced forward-scatter beyond the horizon of otherwise line-of-sight electromagnetic waves. Furthermore, the data testify to the feasibility and remarkable foresightedness of Friend's 1939 proposal to use radio reflections for the continuous sounding of air mass boundaries. Indeed, any number of heretofore invisible meteorological processes appear open to dynamic examination by powerful new radar systems such as the AN/FPS-6. The vast applied and research potential of these devices awaits to be exploited.

Thomas S. Austin (Pacific Oceanic Fishery Investigations, Honolulu, T. H.) *Variations with Depth of Oceanographic Properties along the Equator in the Pacific*—The vertical distribution along the equator in the Pacific of temperature, salinity, density, oxygen, and phosphate, sea surface to 1000 m, and the anomaly of the dynamic height of the sea surface and other isobaric surfaces above the 700 decibar surface are shown. The figures, depicting summer and winter situations, include stations from within one degree of latitude north or south of the equator between 110° W and 135° E longitude. The surface of the sea, relative to the 700 db surface, slopes upward, east to west, approximately 0.8 dynamic m; the value for the slope is 5.0×10^{-8} during both summer (July to December) and winter (January to June). The longitudinal pressure gradient does not extend much below the layer of relatively large vertical density gradient. At the depth of $\delta_t = 26.5$, 250–300 m, relatively little east-west slope is evident during either summer or winter.

In the surface layer (sea surface to top of the thermocline), temperatures along the equator are lower in the eastern Pacific during both seasons; the thermocline is comparatively level west of 160° W–180° longitude, sloping upward to the east. Temperatures are appreciably lower and concentrations of inorganic phosphate are higher in surface layer in the eastern Pacific during the summer, both reflecting the seasonal and longitudinal variations in divergence and upwelling. The oxygen minimum, centered at a depth of approximately 450 m, is a continuous feature from 100° W longitude (eastern limit of the profiles) to 160°–170° E longitude with the lowest concentrations in the east (≤ 0.5 ml/l) increasing to 1.5 to 2.0 at the westward limit. West of 160°–170° E longitude, concentrations at 450 m rapidly increase to 3.0 ml/l.

Leslie F. Bailey (2929 Connecticut Ave., Washington 8 D.C.) and Carl Romney (6012 Wilmett Road, Bethesda 14, Md.) *Seismic Waves from the Nevada Underground Explosion of September 19, 1957*—Pn-waves from the Nevada underground explosion were recorded at stations between 181 and 1023 km. When fitted to a linear travel-time curve, the observations gave the relation $t = 8.0 + \Delta/8.0$. Less definite P waves were detected at distances as great as 17.7° in the United States and at a distance of 33.4° at College, Alaska. At many stations strong short-period (0.5 to 1.5 sec) arrivals were recorded which were identified as Lg on the basis of their observed speed of 3.5 km/sec. Lg tended to be most definite on the vertical-component seismograms.

W. B. Bailey (Fisheries Research Board of Canada, Atlantic Oceanographic Group, St. Andrews, N.B., Canada) *On the Dominant Flow in the Strait of Belle Isle*—In addition to the usual tidal currents in the Strait of Belle Isle, there is, at times, a tendency for the current to set in one direction more than in the other. This over-balance of water movement in one direction is termed the element of dominant flow. The possible causes of this flow are attributed to meteorological factors and to others effecting long-period fluctuations in sea level. Very few extended oceanographic observations have been available to illustrate this phenomenon on a grand scale, particularly for a westerly flow. Observations taken in September 1955 illustrate a dominant westerly flow in considerable detail. This dominant westerly flow was associated with the passage of an intense low-pressure area (Hurricane Ione) from the Gulf of St. Lawrence to the Labrador Sea between September 21–23, 1955.

Emanuel M. Ballenzweig (Office of Meteorological Research, U.S. Weather Bureau, Washington, D.C.) *Formation of Tropical Storms Related to Anomalies to the Long-Period Mean Circulation*—By using composite charts of time-averaged means, many details of the role of the large-scale circulation in influencing the generation of tropical cyclones are brought into focus. First, a contrast is shown between generally propitious and inhibiting conditions for genesis in the broad area of the North Atlantic. The formation of tropical storms is shown to be concentrated in five areas in the Atlantic and the longer-period circulation features accompanying tropical cyclogenesis in a few of these areas is next discussed with the help of a series of charts containing rather clear-cut anomalous features. Conditions favorable for the formation of tropical storms are found to differ among the different areas. The composite charts appear to be useful as guides in the preparation of long-range forcasts of hurricane formation, once the mean circulation has been predicted.

Paul B. Barton, Jr. (U.S. Geological Survey, Washington 25, D.C.) and Philip M. Bethke (Department of Geology, Missouri School of Mines and Metallurgy, Rolla, Mo.) *Approximate Single Ion Activity Coefficients from pH Measurements*—Many individual ion-activity coefficients can be determined to the extent that: (1) the glass electrode gives a measure of the hydrogen-ion activity, and (2) liquid junction potentials are negligible. The procedure consists of measuring the pH (from which a_{OH^-} is calculated) of a series of solutions of varying ionic strength which are in equilibrium with a metal hydroxide or oxide. From each of these a 'constant', $K' = [M^{+2}]a^2_{OH^-}$, is calculated. Extrapolation of K′ to infinite dilution gives the activity product constant, $K = aM^{+2} \cdot a^2_{OH^-}$. The individual ion-activity coefficient, $\gamma\ M^{+2}$, is defined as $a_{M^{+2}}/[M^{+2}]$ which in turn equals K/K'. A related procedure using basic salts in addition to the simple hydroxides is used to obtain data for anions as well as cations. Experimental work with zinc and copper sulfates and chlorides thus far lacks the precision of conventional physical chemical studies, but the data are useful in predicting the effect of chemical environment on the solubility of minerals. Further refinement of this technique may lead to an understanding of the mechanism of transport of ore minerals under hydrothermal conditions.

A. E. Beck and J. M. Beck (University of Western Ontario, London, Ont., Canada) *On the Measurement of the Thermal Conductivity of Rocks by Observations on a Divided Bar Apparatus*—Rapid techniques for the preparation of discs of rock and the determination of rock conductivities have been used to make a large number of measurements on both coarse-grained and fine-grained rocks. Methods in which either sets of discs or single discs can be used are described, and the mean values of conductivity found by combining the results in various ways are compared. The modes of the rocks were found by examination of a thin section for the fine grained rocks or by examination of each disc for the coarse-grained rocks. Conductivities computed by the method of Birch and Clark from the modes were compared with the experimentally determined conductivities; the results indicate that, at least for the coarse-grained rocks, the usefulness of the conductivities obtained from divided bar measurements can be seriously questioned. The reliability of methods of saturating porous rocks are also questioned.

Walter C. Beckmann, Archie C. Roberts, and Bernard Luskin (Lamont Geological Observatory, Columbia University, Palisades, N.Y.) *Sub-bottom Depth Recorder Survey of Western Long Island Sound*—The sub-bottom depth recorder (SDR) has proved to be an extremely valuable tool in mapping the sub-bottom geologic structure of water covered areas. The SDR is essentially a high-power, broad-band, low-frequency echo sounder utilizing an electrical spark discharge as a sound source. Penetration of over 450 ft of sediments in over 50 ft of water in Long Island Sound has been achieved. The basement topography and the depth of several horizons within the sediments have been mapped in Long Island Sound in considerable detail from Throg's Neck to Smithtown Bay. The basement slopes gently southeast, exhibiting various east-west oriented features having a relief of several hundred feet. Physical separation of the sound source and receiver permits one to obtain wide-angle reflections with continually varying distance. This permits a direct determination of sound velocities in the sedimentary layers and enables one to correct the SDR records for this sound velocity in order to determine the true depth of the various intermediate horizons and basement.

Hugo Benioff and Frank Press (Seismological Laboratory, California Institute of Technology, Pasadena, Calif.) *Progress Report on Long-period Seismograph Recording*—Extension of long-period response of seismographs has revealed the existence of important energy components with periods beyond 50 sec. These long waves correspond to propagation types not hitherto recognized. Seismograms are shown illustrating (a) surface reflected body waves (PS_3) traversing the major arc, (b) mantle Rayleigh waves R18 with period 600 sec, (c) unexplained low-velocity long waves ($T = 200$ sec), and (d) long-period waves from relatively small shocks. The significance of the presence of long waves in terms of the source mechanism is discussed.

Instruments now in routine operation are: (a) three-component electromagnetic pendulums, $T_0 = 30$ sec, $T_g = 90$ sec; (b) strain seismograph with displacement transducer condenser coupled to 600-sec galvanometer; and (c) ink-writing tidal-strain recorder. Experimental recordings are being made with the following: (a) electromagnetic pendulum Z, $T_0 = 2.5$ sec, condenser shunt, $T_g = 600$ sec, and (b) electromagnetic pendulum Z, E-W, $T_0 = 80$ sec, $T_g = 90$ sec. Long-period pendulums with displacement transducer, condenser coupled to 600-sec galvanometers, are contemplated.

Kenneth O. Bennington (Department of Geology, University of Chicago, Chicago 37, Ill.) *Energy Transfer during Metamorphic Differentiation*—Recrystallization in zones of high stress and crystal growth in high and adjacent low stress zones produce characteristic structurally separated contemporaneously developed mineral assemblages. The diffusing material during differentiation is assumed to migrate as oxides and hydroxides. Energy transfer is evaluated by pro-rating the heat of formation of minerals among their constituent oxide groups proportionally to the heat of solution of the separate oxides. An individual oxide has different relative energy values in each mineral structure. Recrystallization is accomplished by activating the least stable oxide first. High differential pressure releases oxides in non-equilibrium reactions under endothermic conditions. Their escape satisfies volume reduction requirements, subtracting energy which is transferred to the lower-pressure and exothermic-reaction area of deposition. Diffusing material migrates down a pressure gradient creating an opposed thermal gradient which is caused and sustained by the dynamic structure. The thermal gradient decays as structural deformation ceases, retrograde reactions being a measure of its magnitude. Migration of pressure systems may force acid material from former low-pressure zones into basic residual masses of former high-pressure areas producing exothermic reactions adequate to form basalts. Extending this hypothesis to an Earth model provides the interesting implication of a low-temperature core

Louis Berkofsky (Atmospheric Analysis Laboratory, Geophysics Research Directorate, Air Force Cambridge Research Center, Bedford, Mass.) *Some Preliminary Results of Numerical Hurricane Formation Prediction*—A nongeostrophic flow model, in which the latent heat of condensation released through pseudo-adiabatic processes is the only heat source, is devised. An attempt is made to formulate initial conditions which resemble, as nearly as is known, the conditions existing prior to the formation of a hurricane. Using these initial conditions, the equations are solved on the IBM 704 electronic computer. Solutions are obtained with and without the latent heat of condensation in order to assess the importance of the heating for the development process.

Nedavia Bethlahmy (U.S. Forest Service, Pacific Northwest Forest and Range Experiment Station, P. O. Box 4059, Portland 8, Ore.) *Logging and Surface Runoff*—Modern logging has introduced techniques which affect the hydrologic characteristics and behavior of watersheds. These techniques involve the building of truck and skid roads, and the use of fire as a tool in eliminating logging debris. Investigations have clearly shown that roads, improperly located and poorly constructed, increase stream turbidity and disturb regularity of streamflow. The effect of skid roads is not as well understood, but good planning and attention paid to details of drainage may minimize the deleterious effects of this phase of logging. The hydrologic effects of controlled fires have been studied, but much remains to be learned. Severe burns reduce soil infiltration rates, but such burns normally occur on only a small portion of the logged area. The aggregate hydrologic significance of these severely burned areas must still be evaluated.

E. P. Bialecke and A. A. Dougal (University of Illinois, Urbana, Ill.) *Laboratory Measurements of the Recombination Coefficient of Electrons and Ions in Nitrogen Gas at Very Low Electron Temperatures*—The recombination of electrons and ions in ionized molecular nitrogen gas was studied in well-controlled laboratory experiments. A pulsed electrical discharge of very short duration was utilized to ionize the gas. After the initial ionization, the electron gas thermalized with the molecular gas through collisions yielding an electron temperature equal to the molecular gas temperature. The gas temperature itself was controlled and variable throughout the temperature range from 92 to 300°K, which resulted in mean electron energies of 0.01 to 0.04 electron volt. Radio frequency measurements made in the microwave wave-length range were employed to determine the concentration of electrons and ions as the ionization decreased due to electron-ion recombination. The recombination coefficient α is found to be dependent upon gas pressure p and electron temperature $T\hat{e}$. At $T\hat{e} = 92°K$, α is 1.9×10^{-6} cm^3/sec at $p = 0.2$ mm Hg and α increases to 7×10^{-6} cm^3/sec at $p = 1.35$ mm Hg. α was also determined at several intermediate temperatures; at $T\hat{e} = 300°K$, α is nearly constant at 7×10^{-7} cm^3/sec for $0.1 < p < 3.0$ mm Hg.

Francis Birch (Dunbar Laboratory, Harvard University, Cambridge, Mass.) *Composition of the Crust and Upper Mantle in the Light of Experimental Studies of Wave Velocities in Rocks*—A considerable accumulation of laboratory data, including unpublished measurements, are now available for the interpretation of seismic velocities in terms of rock types or of hypothetical mineral assemblages. The data show a systematic variation of velocity with mean atomic volume for minerals and compounds in which ozygen is the principal anion (oxides, silicates, carbonates) regardless of structural type, once intergranular porosity has been eliminated by compression. These measurements, with allowance for the effect of temperature, are compared with seismic velocities for the crust and upper mantle.

A. K. Blackadar (Department of Meteorology, Pennsylvania State University, University Park, Pa.) *Frictionally Induced Momentum Oscillations and Motion Patterns in the United States*—Owing to variations of surface stress, the momentum of the layer below 2500 m goes through diurnal oscillations which vary in phase and amplitude from point to point. The distribution of these oscillations over the United States is shown for a ten-day period, and the convergence patterns are discussed in connection with the diurnal distribution of thunderstorm frequency.

M. Blaik, J. Northrop, and C. S. Clay (Hudson Laboratories, Columbia University, Dobbs Ferry, N.Y.) *Some Seismic Profiles Onshore and Offshore Long Island, New York*—Seismic velocity determinations in shallow layers (less than 2000 ft deep) have been made recently at an experimental location on the Atlantic Coast. Speed layering indicated by seismic reflection and refraction is compared with short-interval borehole velocity measurements. Reflection profiles were obtained both on a barrier beach using multiple geophone arrays and in the adjoining lagoon, in approximately eight feet of water, using bottomed multiple-hydrophone arrays. An unreversed refraction profile was completed on the beach by varying the shooting distance and receiving with a fixed geophone array. A reversed refraction profile was obtained offshore, in about 50 ft of water, using shots at different distances from a bottomed hydrophone. Although the smoothed velocity distribution data may be closely approximated by a linear increase with depth, significant high-speed and low-speed layers are shown by the borehole interval velocity data. Very little of this detail is evident in the beach refraction data in spite of excellent time and distance control. The offshore refraction profile indicates even less about layers with thicknesses small compared to the depth of the deepest refractor encountered. The reflection profiles yield little or no detail in this respect. Many significant differences are noted between the seismic profile velocities and the borehole velocities. The importance of each of the methods is briefly discussed.

Harry F. Blaney (U. S. Department of Agriculture, 1505 Post Office and Court House Building, Los Angeles, Calif.) *Consumptive Water Requirements of Vegetative Cover in River Basins*—Consumptive use of water by natural vegetation and irrigated crops involves problems of water supply, both surface and underground, and watershed management, as well as those of management and general economics of irrigation and multiple-purpose projects. Consumptive use is the principal factor influencing water yield from mountain watersheds for irrigation and other purposes in arid and semi-arid regions. This paper presents data on consumptive use (evapotranspiration) by natural vegetation and irrigated crops, and it indicates how this information, together with climatological data, may be employed to determine consumptive-use requirements for water in river basins.

L. E. Borgman (5701 Carew, Bellaire, Texas) *An Algorithm for the Ocean Wave Forces on Inclined Cylinders*—After a review of the assumptions in the wave force formula for vertical cylinders proposed by Morison, O'Brien, Johnson, and Schaaf (1950), a formula embodying the same assumptions is advanced for the determination of the wave forces on an arbitrarily oriented cylinder. Essentially the x components of the water particle velocity and acceleration in the vertical cylinder formula are each replaced by the component of the vector (velocity or acceleration) which is perpendicular to the cylinder axis and in the plane common to the vector and the cylinder axis. The resulting equation is expressed in vector and matrix notation. A concise computational procedure which allows the use of either variable or constant coefficients is outlined and a sample calculation is provided.

W. F. Brace (Massachusetts Institute of Technology, Cambridge, Mass.) *Indentation and Plastic Properties of Certain Geologic Materials*—Many apparently brittle rock-forming materials become plastic locally under indentation by a hard object. Plastic rather than brittle behavior is due to the high confining pressure imposed locally beneath the indentor. In the indentation, or 'hardness' test, a diamond ball or wedge is pressed into a smooth surface of the test material, providing one or more points on the conventional stress-strain flow curve, corresponding to strains of eight per cent or more. For materials which are isotropic and do not work-harden, the stress at this strain is the yield stress, and it can be calculated approximately. Results obtained for limestone and rock salt are compared with yield characteristics obtained in more conventional tests by Robertson, Bridgman, and others. Indentation may be used to study plasticity of other materials such as ice, anhydrite, and quartz at various temperatures and strain rates.

R. R. Braham, Jr. (Department of Meteorology, University of Chicago, Chicago, Ill.) *Cloud Duration as an Important Parameter in Cloud Seeding*—One of the disturbing aspects of experiments for increasing precipitation through the use of silver iodide smokes or dry-ice pellets is the apparent lack of consistency between the results of basic laboratory experiments and the results of seemingly similar experiments carried out in the atmosphere. Although seeding trials on subcooled stratus largely repeat laboratory results, the results obtained from seeding subcooled cumuli are far from convincing. Cumulus cloud-seeding experiments carried out by the University of Chicago group gave inconclusive results in spite of a very careful control which permitted an assessment of artificially induced rain as opposed to natural rain. Further study has shown that one of the most serious obstacles to assessing seeding effects in cumulus clouds concerns the duration of clouds suitable for seeding.

To be usable for ice-nuclei seeding a cumulus cloud must remain subcooled for a period long enough to permit the ice nuclei to grow to precipitation sizes. Studies of cloud lifetimes showed that the lifetimes of most cumuli in the subcooled state are approximately equal to the time required for seeding to become effective. Therefore, seeding can be detected only in clouds having a longer than average life. It is in such clouds, however, that the probability of natural rain reaches values approaching unity. Because of these circumstances an inordinately large sample size is required in order to find seeding effects. As a corollary, results obtained by seeding a small number of cumuli must be suspect. A new experimental design for controlled seeding of cumuli is suggested.

R. R. Braham, Jr., E. L. Harrington, and T. E. Hoffer (Department of Meteorology, University of Chicago, Chicago, Ill.) *Use of Refractive Index Turbulence for Estimating Mechanical Turbulence in the Atmosphere*—From a series of in-flight measurements supplied by the Air Force, an analysis has been made of fine structure variations of refractive index around a group of about 70 cumulus clouds. The original data were obtained in the vicinity of the Bahamas on June 15 and 19, 1956. The data were evaluated in terms of RI gradients, making use of a mechanical read-out device for determining the differences in RI and time between successive pairs of significant points in the RI trace. Significant points are defined as points of maxima, minima, and major changes of slope. System accuracy permitted evaluation of RI differences with a precision of about 0.1 N unit and horizontal distances (from airspeed and time differences) to about three meters.

Frequency distributions of RI gradients were prepared for each level of flight and for clear air, cloud core, and regions of transition at the cloud boundaries. The standard deviations of these frequency distributions are measures of the intensity of the refractive index turbulence and were found to be different for various levels and positions with respect to the cloud cores. From the standard deviations of the frequency distributions and from representative values of the horizontal distance over which the gradients extended, it was possible to infer a statistic roughly analogous to the 'mixing lengths' of classical mechanical turbulence theory. Such an approach offers promise of providing information about mechanical turbulence on a scale and to a degree of precision hitherto unattainable.

D. L. Brakensiek (Watershed Technology Research Branch, Soil and Water Conservation, Agricultural Research Service, Coshocton, Ohio) and R. K. Frevert (Agricultural Engineering Department, Iowa State College, Ames, Iowa) *Estimation of Storm Surface Runoff by Infiltration Theory*—Equations with antecedent rainfall as the independent variable were obtained for estimating the parameters of the infiltration capacity equation developed by Horton. The data of this study permitted estimation equations to be developed for a Marshall silt loam-corn, small grain, and legume-grass complex. The derived estimating equations together with a superimposing procedure as outlined by Cook were used for estimating runoff from gaged watersheds in the northwest Iowa study area. Comparing estimated rainfall excess with measured runoff indicated reasonable success. Certain points were discussed which might be considered in future infiltrometer tests. In particular, the possibility that the so-called wet infiltrometer run may simulate unrealistic runoff potentials was considered.

Glenn W. Brier and Isadore Enger (Office of Meteorological Research, U.S. Weather Bureau, Washington, D.C.) *Weather Probabilities Several Months in Advance and Possible Operational Use*—As indicated by the recent "Statement on Weather Forecasting" issued by the American Meteorological Society, it is generally believed that forecasts for more than a few weeks or a month in advance have little or no reliability. Therefore, any rational or systematic long-range planning that takes weather into account must be based primarily upon probabilities provided by climatological analysis. The extent to which these normal climatological probabilities can be modified by a particular prediction scheme will determine its operational usefulness. Even though a prediction method has relatively little skill, an analysis of the problem discloses that its potential usefulness is greatest for those operations most affected by rare or extreme events. A few typical series of monthly mean temperatures have been treated statistically to determine whether there is any predictability beyond one month. Preliminary results show promise that quantitative predictions more useful than climatology can be made regarding the occurrence or non-occurrence of an extreme event within periods ranging up to four or five months in the future.

Charles L. Bristor (Joint Numerical Weather Prediction Unit, Suitland, Maryland) *The Effect of Data Coverage on Forecast Accuracy*—Networks of data were simulated by interpolating height and wind from a hypothetically 'correct' analysis at a uniform array of points. The interpolated values were added to random numbers whose statistics are typical of nonsystematic errors of observation, and were then regarded as genuine data. Such artificially constructed 'data' for several networks of different densities were analyzed independently. The differences between these analyses and the hypothetically 'correct' analysis were taken to be representative of the initial analysis error under conditions of varying station density. Numerical forecasts were computed from the different analyses and compared with the forecast made from the 'correct' initial data. Several such comparisons indicate that initial analysis errors do not grow to an important degree so long as the spacing between synoptic reports confines error fields to a scale smaller than that of the synoptic disturbances. However, with data spacing comparable with that over existing regions of poor data coverage, initial errors are amplified twofold in a 48-hour forecast interval.

Further experiments, in which the data were analyzed objectively, were carried out to eliminate inconsistencies of analysis. Limited experiments of the same type are also discussed from the standpoint of baroclinic instability.

W. S. Broecker (Lamont Geological Observatory, Columbia University, Palisades, N. Y.), K. K. Turekian (Yale University, New Haven, Conn.), and Bruce C. Heezen (Lamont Geological Observatory, Columbia University, Palisades, N.Y.) *The Relation of Deep-sea Sedimentation Rates to Variations in Climate*—Variations in sedimentation rates with time have been investigated in mid-equatorial Atlantic core (A 180–74). Measurements of C^{14}/C^{12} ratios, per cent coarse fraction ($>74\ \mu$), and per cent calcium carbonate at frequent depth intervals permit the calculation of absolute rates of sedimentation for each of the major contributors to the sediment. The rates of deposition of both the carbonate and clay fractions are shown to decrease abruptly from the high glacial rate approximately 11,000 years ago. The observed correlation of sedimentation rate with surface ocean temperature and extent of continental glaciation permits the dating of late Pleistocene events by reasonable extrapolations beyond the limits of radiocarbon dating. The beginning and end of the warm period preceding the last cold surface ocean water period are estimated at $\sim$ 150,000 and 70,000 years respectively.

W. S. Broecker and A. Walton (Lamont Geological Observatory, Columbia University, Palisades, N. Y.) *C^{14}/C^{12} Ratios in Fresh Water Systems*—Radiocarbon age determinations on fresh-water carbonate materials are based on the assumption that an accurate estimate can be made of the C^{14} concentration at the time of deposition. C^{14} analyses of materials formed in fresh water will allow this assumption to be more adequately defined and also provide information about the CO_2 cycle in fresh water systems. It has been shown that underwater plants, shells, and fish collected from the river-lake systems of the Great Basin provide an accurate estimate of the C^{14}/C^{12} ratio of dissolved carbonate. In addition, the C^{14}/C^{12} ratio in river waters generally decreases with increasing carbonate content and the lakes have a C^{14}/C^{12} ratio greater than the river water supplying the lake. These data allow an estimate to be made of the rate of exchange of the carbonate in the lake with the CO_2 in the atmosphere. Although some uncertainty is introduced in the result because of the ten per cent increase in the C^{14}/C^{12} ratio in atmospheric CO_2 which has occurred during the past four years, repeated measurements over a number of years will allow more accurate values to be obtained.

Howard Busch and G. Robert Hall (Soil Conservation Service, 6816 Market St., Upper Darby, Pa.) *Land Use Trends of the Brandywine Watershed*—This paper discusses land use changes and trends which have been observed in the Brandywine Watershed (Pennsylvania and Delaware) in recent years. The application of conservation practices, less intensive use of farm lands, urbanization, and other factors which influence sediment yield are presented. Land use data from soil survey maps and Soil Conservation Service records, and from other sources, are used as a basis for the study.

C. M. Carmichael and R. J. Uffen (University of Western Ontario, London, Ont., Canada) *Remanent Magnetization of Some Allard Lake Ilmenites*—In the Allard Lake region of Quebec (lat 52°N, long 63°W) there are numerous deposits of Ilmenite which are known to be reversely magnetized from anomalies in the Earth's magnetic field as measured by an airborne magnetometer. The directions of the remanent magnetic field of samples taken from both negative and positive anomaly regions have been measured using an astatic magnetometer. It is found that there is a wide variation in directions of the remanent fields of these samples. Both normal and reversed samples are found in the same, and apparently homogeneous deposit.

James H. Carpenter (Chesapeake Bay Institute, Johns Hopkins University, Baltimore, Md.) *The Solubility of Oxygen in Water*—The recent measurements of Truesdale, Downing, and Lowden for distilled water were confirmed, except above 30°C where their data were not adequate. Equilibration techniques were compared and violent shaking was found to cause supersaturation of less than one per cent and only at low temperatures. These observations suggest that the anomalous results of Fox are due to causes other than supersaturation created by agitation. A rapid equilibration technique is shown to be valid and recommended for the study of water having an appreciable B. O. D.

(Table for Catanzaro-Gast abstract on p. 510)

Locality	Pb^{204}/Pb^{206}	Pb^{207}/Pb^{206}	Pb^{208}/Pb^{206}
Christmas Lake Pegmatite, Beartooth Range	0.0712 ± 0.0011	1.060 ± 0.010	2.37 ± 0.02
Blackstone Lake Pegmatite, Beartooth Range	0.0702 ± 0.0008	1.047 ± 0.008	2.34 ± 0.02
Glendale Pegmatite, Black Hills	0.0621 ± 0.0007	0.959 ± 0.008	2.20 ± 0.02
Crystal Peak Pegmatite, Pikes Peak, Colo.	0.0604 ± 0.0010	0.921 ± 0.008	2.18 ± 0.03
Morefield Pegmatite, Amelia Courthouse, Va.	0.0553 ± 0.0007	0.860 ± 0.008	2.10 ± 0.02
Bonneville, Wyoming	0.0605 ± 0.0007	0.937 ± 0.006	2.06 ± 0.02
Bob Ingersoll Pegmatite, Black Hills	0.0607 ± 0.0012	0.926 ± 0.010	2.10 ± 0.02

E. J. Catanzaro and P. W. Gast (Lamont Geological Observatory, Columbia University, Palisades, N. Y.) *Isotopic Composition of Lead in Pegmatitic Feldspars*—The study of time-dependent variations in the isotopic composition of lead requires lead samples of known age. Inasmuch as pegmatites can be dated by several independent means and contain microcline with a negligible uranium and significant lead content, they provide an opportunity for the study of these time-dependent variations. Microclines from a number of dated localities have been analyzed. The isotopic compositions are given in the table below. The isotopic compositions of the first five samples are in accord with the model derived from ore leads. The Ingersoll and Bonneville samples appear to contain anomalous lead.

Joseph W. Chamberlain (Yerkes Observatory, University of Chicago, Williams Bay, Wisc.) *The Present State of Speculation about the Origin and Acceleration of Aurora-Producing Particles*—For many years there has been a paradox in the velocity of propagation of solar particles as deduced from delay times between solar and geophysical events compared with the velocity of (at least some) auroral particles that would be required for their penetration to the lower auroral heights. More recently, analyses of the broadened hydrogen lines in auroral spectra have indicated that most of the incident protons initially have speeds considerably less than would be required to reach the bottom of an auroral arc, although there is observational evidence that protons do reach the bottoms of the arcs. Therefore, in order to explain the hydrogen-line data consistently, a dispersion in the velocities of incident protons seems necessary. Further, high-altitude balloon experiments have disclosed x-rays evidently associated with aurorae and magnetic storms and most probably produced by electrons incident with speeds exceeding one-third the speed of light. (In the auroral zone fast electrons are regularly present at rocket altitudes.)

These results suggest that auroral particles are accelerated to high speed in the neighborhood of the Earth. Various acceleration schemes include electric fields, betatron effect, and Fermi's mechanism. An alternative interpretation of the velocity dispersion supposes that the particles travel to earth in a magnetized cloud; individual particles may have high energy through rapid spiraling about the lines of force in the cloud while the cloud as a whole travels through space with moderate speed.

The observation of increased x-ray flux when rayed structures are enhanced might be interpreted in terms of either of two processes for producing rays. The x-rays may simply indicate the entry of fast electrons, which produce rayed features directly. This mechanism is supported by the rough agreement of the electron energy deduced from the Bremsstrahlung x-rays with that required to reach the lower auroral altitudes. As in the case for incident protons, there would probably have to be a velocity dispersion in the electrons to explain the long luminosity curves of rays. Alternatively, rays may be a product of an electric field, which accelerates atmospheric electrons to energies of several ev while it accelerates extraterrestrial electrons to 50 kev. The rays themselves would then arise from the atmospheric discharge rather than from the high-energy electrons.

Sydney Chapman (Geophysical Institute, College, Alaska, and High Altitude Observatory, Boulder, Colorado) *The Terrestrial Implications of Thermal Conduction in the Solar Corona*—The Sun has an outer atmosphere, visible during solar eclipses, called the corona. It is at an astonishingly high temperature, of the order of a million degrees centigrade, whereas the disc of the Sun as we ordinarily see it has a far lower temperature, of a few thousand degrees. The cause of the high temperature of the corona is still uncertain. The corona varies with time, according to the degree of activity on the Sun as shown by sunspots and flares. The coronal gas consists mainly of protons and electrons, the components of sundered atoms of hydrogen, which is the main constituent of the Sun. In addition, there is helium and, surprisingly, a small proportion of very highly ionized metallic atoms. The corona emits x-rays and radio waves. When the Earth's motion brings the Sun nearly in line with cosmic radio sources, the cosmic radio waves are modified; this shows that the corona extends at least several solar radii beyond the Sun.

A study of the temperature and density distribution in the corona has been made by the author on the assumption of a static corona distribution uniformly around the Sun, though eclipse and other photographs show that often the corona has considerable local irregularities in it. The study revealed that the corona must extend over the whole space traversed by the planets, even beyond Neptune and Pluto. It remains hot up to those great distances; at the distance of the Earth, its temperature is of the order 350,000°F, and its density may be 1000 protons and 1000 electrons per cubic centimeter.

The Earth and Moon move through this hot gas, and heat must be conducted from it into the Earth's atmosphere. In the upper ionosphere, the F_2 layer, there is a downward flow of heat, and this appears to be more than is provided by the solar energy of ultraviolet light absorbed in that layer. This downward flow of heat, it is suggested, comes from the hot coronal gas surrounding the Earth. The Earth's magnetic field at high levels hinders this flow of heat in equatorial regions, but the heat can flow freely towards the magnetic poles. Between the F layer and the coronal gas there is probably a layer of nearly neutral atomic hydrogen, several tens of thousands of kilometers thick. In this layer a world wide circulation is likely to be set up that equalizes the flow of heat downwards into the ionosphere.

These studies greatly modify our conceptions of the outer atmosphere, which must extend many earth-radii above the Earth, far beyond where the atmosphere has previously been thought to end. This extended atmosphere is traversed by natural radio signals called whistlers, generated by thunderstorms in the Earth's lower atmosphere; these whistler signals can travel along the Earth's magnetic lines of force to heights of many thousands of kilometers above the equator, and bounce back and forth between the northern and southern hemispheres. Studies of whistlers made in the United States tend to support these new Ideas about the Earth's outermost atmosphere. Further support is given by studies of the zodiacal light.

J. E. CHAPPELEAR (Shell Development Company, Houston, Texas) *The Calculation of Wave Forces on Groups of Vertical Cylinders*—A method of calculation of wave forces on groups of vertical cylinders subject to wave action is presented. The assumptions employed are: (1) The assumptions of boundary layer theory are correct; that is, the effect of the viscosity is confined to regions very close to surfaces and elsewhere we have potential flow; (2) the ratio of the wave height to wave length is small (Airy theory); (3) the ratio of the wave length to the various dimensions of the configuration of the cylinders (the center to center distances) is large; and (4) the ratio of the center to center distances to the various radii is large. The calculation of the potential flow velocity distribution is then made. The result obtained is that only the magnitude of the velocity distribution and the location of the stagnation points are changed from the potential flow distribution around a single cylinder. By arguing that similar configurations should produce similar effects, it is then possible to calculate geometrical correction factors for the drag and inertial coefficients for a single cylinder. Certain examples involving a small number of cylinders in simple geometrical arrays are presented to illustrate the application of the method, and a brief discussion of the experimental evidence is given.

EDWIN J. CHERNOSKY (Geophysics Research Directorate, Air Force Cambridge Research Center, ARDC, Bedford, Mass.) *Geomagnetic H Intensity before and after a Disturbed* (*5D*) *Day*—The values of the magnetic horizontal component intensity H for days of given activity relative to those of selected reference days are studied. The reference day is each of five magnetically most disturbed (*5D*) days of each month that is not immediately preceded by another *5D* day. The difference in H between the reference day and another selected day is allocated to a group designating the number of days intervening between the two days, then studied. The other selected day is chosen in different tests, as being (a) one of the five most quiet (*5Q*) days (b) another *5D* day. The means of each group of any type days from 14 days before to 14 days after the reference day are examined also. In the Cheltenham data (1927–30) the H values are found to be higher in the two or three days preceding the reference day than in almost any of the following 14 days. The post-disturbance increase in H occurs only for the first eight or so days. Since the horizontal intensity is greater just before magnetic disturbance than in the following 14 days, either (a) H does not completely recover within the 14 days or (b) H increases in the days just prior to most disturbance decreases in H and the increase is an integral part of the disturbance mechanism. As disturbances most frequently follow themselves in less than 14 days, with corresponding recovery times, the alternative statement (b) is supported, and thus requires serious consideration.

LLOYD A. CLARK (McGill University, Montreal, Canada, and Geophysical Laboratory, Carnegie Institution of Washington, Washington, D.C.) *Phase Relations in the System Fe-As-S*—The phase relations in the Fe-As-S system at 600°C, studied in rigid silica tubes where a vapor phase is always present, are as follows: A liquid field extends along the S-As join from 100 to 22.8 ± 0.2 weight pct sulfur. An extensive pyrite-liquid field and a narrower pyrrhotite-liquid field are separated by the three-phase triangle pyrite-pyrrhotite-liquid in which the composition of the liquid is approximately 34 pct sulfur, 66 pct arsenic, and <0.1 pct iron. In the assemblages pyrrhotite-arsenopyrite-liquid and arsenopyrite-arsenic-liquid the compositions of the liquids are similar, and are close to the point of arsenic saturation. Arsenopyrite-arsenic-loellingite ($FeAs_2$), pyrrhotite-arsenopyrite-loellingite, pyrrhotite-loellingite-FeAs, pyrrhotite-FeAs-Fe_2As, and FeS-Fe_2As-Fe are also stable assemblages. The phases FeAs and Fe_2As are not found in nature. Many of the three-phase assemblages are presumed to be separated by very narrow two-phase regions whose limits have not so far been accurately defined. Pyrrhotite and loellingite have small fields of ternary solid solution. With increasing temperature between 650° and 750°C first arsenopyrite, and then pyrite, becomes unstable. At temperatures below 450° to 500°C the assemblage pyrite-arsenopyrite becomes stable. Arsenopyrite is synthesized in the presence of excess arsenic and a S-As liquid. Variations in the arsenopyrite unit cell dimensions indicate a limited variation in the composition of this phase.

W. E. COBB AND GILBERT D. KINZER (Office of Physical Research, U.S. Weather Bureau, Washington, D.C.) *Laboratory Measurements of the Growth of Cloud Droplets*—Water droplets initially two microns in radius were held stationary for observation in an upward streaming cloud and were found to grow by accretion. The rate of increase in the radius of individual droplets was measured from four to 65 microns. The free water content and the temperature of the parent cloud were approximately 3.5 gm m^{-3} and 22°C, respectively. Two types of distributions were employed: the first with 80 pct of the free water contained in droplets 5.5 to 8.0 microns in radius; and the second with the free water distributed more widely among droplets 3.9 to 10.4 microns in radius.

W. COMPSTON AND S. EPSTEIN (California Institute of Technology, Pasadena, Calif.) *A Method for the Preparation of Carbon Dioxide from Water Vapor for Oxygen Isotope Analysis*—A method is described for the preparation of carbon dioxide from small amounts of water (ca. 10 mgm) for oxygen isotope analysis. Water vapor is reduced by a mixture of iron and carbon at 500°C, which releases hydrogen without producing a significant amount of carbon monoxide. The iron oxide thus formed is then reduced by the carbon in the same furnace by raising the temperature to 1000°C, and the resultant carbon monoxide catalytically converted to dioxide over nickel. The method has been applied to a determination of the isotopic fractionation factor at 25.4°C between liquid water and carbon dioxide gas. The value found, 1.0407 ± 0.0003, is in good agreement with a determination by an independent method, 1.0410 ± 0.0002. Preliminary data for a second application, study of the isotopic composition of atmospheric water vapor, is also given.

L. F. Conover (Hydrologic Services Division, U.S. Weather Bureau, Coral Gables, Fla.) *Sub-Tropical Clouds as Shown by Time-Lapse Photography*—The behavior of some sub-tropical clouds is shown by 16-mm time-lapse, color photography. Included is the life cycle of a precipitating cumulus as it grows through a stable environment only to be quickly dissipated; the formation of a strato-cumulus deck at twilight; the evaporation of cumuli as they reach the coastline before noonday heating changes the cloud regime; rotation within cloud streets; a cumulo-nimbus shaft showing rotation and the turbulence of the underside of a roll cloud.

H. H. Cooper, Jr. (Ground Water Branch, U.S. Geological Survey, Tallahassee, Fla.) *An Hypothesis Concerning the Dynamic Balance of Fresh Water and Salt Water in a Coastal Aquifer*—Explanations of the dynamic equilibrium between salt water and fresh water in a coastal aquifer commonly assume that the salt water is static. A consideration of some observed phenomena indicates, however, that the salt water moves in a continuous cycle from the sea to the zone of diffusion and back to the sea. This cycle acts to lessen the extent to which salt water occupies an aquifer. The cycle is believed to be energized principally by the to-and-fro motion of the water resulting from ocean tides, fluctuations of fresh-water head, and other forces. The cycle becomes effective as some of the salts in the sea water are transferred to the seaward-flowing fresh water through the process of dispersion in the zone of diffusion. The sea water, lightened by loss of some of its salts, thereupon returns along an upward path to the sea.

Robert M. Cunningham (Aerosol Physics Laboratory, Geophysics Research Directorate, Air Force Cambridge Research Center, Bedford, Mass.) *Details of Atmospheric Structure in and Around Bahaman Cumulus*—Measurements of temperature and humidity with high response equipment (vortex resistance wire thermometer and microwave refractometer) are presented and discussed. These measurements were taken from a B-29 aircraft flying in and around island and ocean cumulus congestus in the Bahamas. Measurements in the short growing stage of cumulus and cumulus bubbles are compared with the dissipating stage. The quasi steady upward flow under the cloud system is described and tentatively related to the periodic almost explosive growth of some of the cumuli.

Leo R. Davis and Otto E. Berg (U.S. Naval Research Laboratory, Washington 25, D.C.) *Rocket Measurements of the Electron and Ion Fluxes in an Aurora*—Energetic ions and electrons have been detected on a rocket flown through a visible aurora. The rocket was fired at 22h 19m CST on January 25, 1958 at Fort Churchill, Canada. The rocket reached a peak altitude of 178 km and passed through a region of the sky covered by a diffuse surface of intensity I. The instrumentation included three scintillation counters, one which measured the total energy flux of electrons of energy greater than 8 Kev and ions of energy greater than about 30 Kev, one which measured the flux of electrons of energy greater than 8 Kev, and one which measured the flux and energy spectrum of ions having energies greater than about 30 Kev. The following results were obtained. (1) The electron flux about 120-km altitude was 1 to 2.5 (erg cm^{-2} sec^{-1} $sterad^{-1}$) and few if any of the electrons penetrated below 85 km. (2) The ion energy flux was about one-hundredth the electron flux, consisted of ions having energies between 50 and 300 Kev, and was absorbed between the altitudes 96 and 112 km. Preliminary analyses of the directional behavior of the particle fluxes above 120-km altitude shows that both the electrons and ions were roughly isotropic over the upper hemisphere.

Aniruddha De (Princeton University, Princeton, N.J.) *Observations on the Deformation Lamellae in Quartz of Four Indian Tectonites*—Well developed deformation lamellae in quartz of two deformed pebbles from a meta-conglomerate, and a quartz-mica schist from Kharsawan, and of a calcareous quartzite from Darjeeling, India, have been studied. The measured angle between optic axis and lamella pole of each grain show that commonly lamellae form at 10° to 15° from the basal plane, as also near ω and d planes of quartz, while lamellae near s, x and m may also be represented. This angle has typical characteristic values for different optic axes maxima in two specimens; the optic axes maxima for grains with and without lamellae in one specimen are mutually exclusive. Crystallographic relation of a lamella tested by another lamella or fracture occurring in the same quartz grain show that the majority of the lamellae could be assigned to $[11\bar{2}0]$ or $[10\bar{1}0]$ zones. The angle formed by two lamellae poles at optic axis in a quartz grain might be 0°, 30°, or 60°; when this is 0° the lamellae have a common direction in the basal plane, which might serve as a common glide line. The variations in the orientation of deformation lamellae with different optic axes pattern suggest that the pre-existing optic axes orientation and the spatial orientation of the lamellae forming stress determine the angular distance of the resulting lamellae from the optic axis.

Hal P. Demuth (U.S. Coast and Geodetic Survey, Washington 25, D.C.) *Applications of the Tellurometer*—This paper will discuss applications of the Tellurometer to specific projects in the U.S. Coast and Geodetic Survey. The project on Atka Island, Alaska will be presented, as well as the present work in Virginia and Maryland on the Federal Highway Program. Some information concerning the accuracy of the instrument both on single-line measurements and traverse lines will be discussed.

Robert B. Dewey (Department of Geology, University of Chicago, Chicago 37, Ill.) *Traction at Wave Velocity Discontinuities*—Experiments have been done to examine a mechanism of producing traction at an interface because of surface waves in that interface. Results showed that the medium of lower wave velocity moved toward the source of retrograde Rayleigh waves. More complex wave systems in a brass plate overlain by incompetent materials such as mixtures of sand and kaolin or finely ground talc produced a number of flow systems and structures among which were low-angle thrust faults. Since the whole fault surface is, in this model, the motor or source of traction, there was no tendency of the thin hanging wall to fold or deform. Thrust produced folds in talc accompanied by differentiation of the talc-air mixture into thin layers of more compacted talc separated by lenticular bubbles of air. These occupied fold cores. These experiments are interpreted as a possible mountain building mechanism.

F. W. Dickson (Division of Physical Sciences, University of California, Riverside, Calif.) *Zone Melting as a Mechanism of Intrusion: A Possible Solution of the Room and Superheat Problems*—Fugitive components (chiefly water) of rock melts, subjected to pressure gradients induced by gravity, diffuse toward lower pressure regions. Melt at the base of a magma column loses water, raising the freezing temperature. Melt at the top gains water, lowering the freezing temperature. Crystallization of minerals at the base releases energy which migrates upward with fugitive components. Country rock surrounding upper portions of the column, subjected to high water pressures at high temperatures, liquifies. The zone melting rises in the Earth's crust followed by the zone of crystallization, which approaches and eventually reaches the liquid-country rock interface in cooler parts of the crust. The process stops because of heat loss or endothermic reactions involving country rock. Efficient use of the original energy has allowed the passive emplacement of a column of plutonic rock, with only a part of the column having been liquid at any given time.

R. R. Doell (Massachusetts Institute of Technology, Cambridge, Mass.) *Paleomagnetic Interpretations*—Recent paleomagnetic pole determinations combined with previous studies may now indicate the following: (1) No continental drift has taken place since the lower Eocene, with little evidence for such drift since the Permian. (2) The 'dipole' hypothesis concerning coincidence of magnetic and axial poles might be questioned. (3) There is a strong need for very careful stratigraphic control in future paleomagnetic studies.

Ralph J. Donaldson, Jr. (Aerosol Physics Laboratory, Geophysics Research Directorate, Air Force Cambridge Research Center, Bedford, Mass.) *Radar Echo Characteristics of Hailstorms and Other Severe Thunderstorms*—Thunderstorms within range of the Blue Hill (Milton, Mass.) CPS-9 radar during 1956 and 1957 were examined quantitatively for echo characteristics capable of identifying storms with hail or damaging winds or both. Reports on surface conditions were received from a network of over 300 volunteer observers. Each reported storm experience was associated, when possible, with the maximum height and maximum radar reflectivity of the particular echo found at the time and place of the storm experience. Reports of hail and damaging winds were associated with a significantly higher average of echo height and radar reflectivity. Although there was no dichotomy in echo features between reports of hail and those with no hail, a useful estimate of the probability of hail was derived from a consideration of both maximum echo height and maximum radar reflectivity. Furthermore, the most severe damaging windstorms and tornadoes were found in the region of high hail probability.

William L. Donn and William T. McGuinness (Lamont Geological Observatory, Columbia University, Palisades, N.Y.) *Seiches in Grindavik Harbor, Iceland*—As part of the IGY Island Observatories program, a conventional tide gage was installed in Grindavik Harbor. The coastal configuration and harbor dimensions are such that the harbor acts as a natural model basin undergoing a 12-ft range in water level twice daily. The period of the ever-present seiche is a function of water level and varies from 4 to 11 minutes with each tide cycle. Observed and theoretical periods correlate very well for the tide range at Grindavik. The amplitude of the seiche is a function of wind direction and intensity with maximum amplitudes occurring when the wind is parallel to the long dimension of the harbor channel. Oscillations of longer and more irregular period occur occasionally at higher stages of the tide. These can be explained by the seiche involving the large flooded shoal area in back of the harbor.

Frederick J. Doyle (Ohio State University, Columbus, Ohio) *Place for Geodesy in the University Curriculum*—Education in surveying, geodesy, and photogrammetry has traditionally been included in civil engineering. During the past several decades the increasing technology in civil engineering has required that courses not directly applicable be diminished, or dropped, from the curriculum. Foremost among these casualties have been courses in geodesy. This trend is continuing, so that today it is impossible to obtain a comprehensive education in geodesy within the confines of a civil engineering department anywhere in the country. To meet this need there is a requirement for a curriculum in the mapping sciences which would be separate from, and on a par with that of civil engineering.

Maurice Dubin (Air Force Cambridge Research Center, Bedford, Mass.) *Measurements of Meteoritic Impacts on Explorer I*—The first satellite launched in the United States during the International Geophysical Year contained an impact microphone to detect collisions of micrometeorites with the cylindrical shell of the satellite. The physical basis of the experiment and a description of the experiment is presented. The objective of the experiment is the measurement of the spatial density of interplanetary matter in the vicinity of the earth by measuring the mass influx of material onto the Earth's surface. The calibration of the equipment to determine its overall sensitivity is described. A very limited amount of telemetered data has been received and examined. These data have been used in the computation of preliminary value for the influx rate of cosmic dust upon the Earth. A comparison of this measurement with values determined by indirect methods will be made. The possible geophysical significance of these measurements will also be reviewed.

Laurence E. Eber and Oscar E. Sette (Bureau of Commercial Fisheries, U.S. Fish and Wildlife Service, Stanford, Calif.) *Indices of Variations in Strength of Atmospheric Circulation over the North Pacific Ocean*—A recent activity, Ocean Research, has been started on the Pacific Coast by the U.S. Fish and Wildlife Service for studying the large natural fluctuations in the abundance and availability of our major ocean fisheries. While defining the problem lies in the field of fishery biology, its solution lies mainly in the domain of oceanography. The study of oceanographic variations is logically inseparable from the study of meteorological variations, and the latter occupies a prominent place on our program. Monthly mean sea level pressure charts have been used to study ocean-wide fluctuations in atmospheric circulation. Pressure gradients at 36 locations oriented with reference to the principal branches of the ocean circulatory system were measured from the charts for a 32-year period. Mean monthly means and standard deviations were computed to determine the seasonal range and variability of gradient values in different regions. Smoothed time series of the data suggest stronger northerly geostrophic wind components on the eastern side of the Pacific for the past decade as compared with earlier years. No evidence of trends was found for the westerlies or trades. Correlation coefficients were computed which compare fluctuations in gradients representing the westerlies with those in other parts of the Pacific.

Floyd C. Elder and Donald J. Portman (Willow Run Laboratories, Engineering Research Institute, University of Michigan, Ypsilanti, Mich.) *Some Measurements of Atmospheric Radiation at Colorado Springs and at the Summit of Pikes Peak*—In September 1956, some continuous measurements of atmospheric, terrestrial, and solar radiation were made near Colorado Springs, Colorado. Simultaneous measurements of total hemispheric radiation were made at the summit of Pikes Peak. A direct measure of the downward flux of radiation from the atmospheric layer below the elevation of the peak was thus obtained. Radiosonde observations, taken at six-hour intervals throughout the period, provide data for computation of the downward flux of radiation from both the total atmosphere and from the atmospheric layer below Pikes Peak through the use of radiation diagrams. A comparison between the measured and computed values of radiation is presented. Instrumentation is described.

William P. Elliott (Atmospheric Analysis Laboratory, Geophysics Research Directorate, Air Force Cambridge Research Center, Boston, Mass.) *The Area within a Concentration Isopleth for Diffusion of SO_2 from a Continuous Point Source*—Concentration measurements taken in the summer of 1956 during Project Prairie Grass were analyzed to find the area within selected concentration isopleths. An empirical relationship between these areas and the value of the concentration, adjusted for source strength and mean wind speed, was determined. This analysis yields an exponential relationship between area and adjusted concentration. The coefficient and the exponent are both related to atmospheric stability in a quasi-predictable fashion.

Isadore Enger (Office of Meteorological Research, U.S. Weather Bureau, Washington, D.C.) *The Period of Time Required to Determine a Daily Normal*—Estimates of the daily normal are made by varying the number of years used to compute daily means and the number of days over which to smooth them. The estimates are then used as climatological 'predictions' one, five, and nine years ahead. The estimate making the best 'predictions', as measured by the root mean square error, is taken to give the optimum period of time to determine a daily normal. Daily maximum temperatures at ten stations in the United States are analyzed in this fashion and the results presented in a series of charts. Some remarks on trends and singularities are made.

Edward S. Epstein (Pennsylvania State University, University Park, Pa.) *The Three-Dimensional Field of Motion in the Lower Stratosphere*—Case studies of the fields of vertical motion in the lower stratosphere have been made by means of an improved version of the adiabatic method. The relations between vertical motion and horizontal flow are described both north and south of the stratospheric warm belt. An attempt to attribute explosive stratospheric warmings entirely to dynamic instability is also described.

Oskar Essenwanger (National Weather Records Center, U.S. Weather Bureau, Asheville, N.C.) *Frequency Distribution of Precipitation in a Logarithmic Scale*—The linear scale is often used for frequency distributions of precipitation data. The statistical approach for these distributions is briefly discussed and compared with results obtained using a logarithmic scale. The latter permits more precise climatological description and understanding of precipitation frequency. Fifty years of Asheville, North Carolina, precipitation record (hourly, six-hourly, daily, monthly, yearly amount) serves as a sample. The theoretical statistical reasons for using a logarithmic scale are also briefly discussed.

E. L. Fireman (Smithsonian Astrophysical Observatory, Cambridge 38, Mass.) *A^{39} in the Sikhote-Alin Meteorite and Its A^{39}-A^{38} Age*—The radioactive isotope A^{39} (260-year half life) is measured in the Sikhote-Alin meteorite which fell in February 12, 1947. For the dated fall the A^{39} can be combined with its A^{38} content to give a measure of its cosmic-ray exposure time. Two Sikhote-Alin samples (7g and 50g) gave 4.8 ± 0.3 A^{39} decays/g day with the activity proportional to the weight. This is the first measurement of A^{39} in a meteorite. No A^{39} is detectable in the Carbo meteorite. Two Carbo samples (6g and 30g) gave 0.05 ± 0.15 A^{39} decays/g day. The He^3 content of Sikhote-Alin was measured to be 4×10^{-7} cc/g; the He^3 content of Carbo was measured to be 4×10^{-6} cc/g. The A^{38} content is approximately $1/12$ of He^3 content. If the assumptions of equal A^{39} and A^{38} cosmic-ray production and constant cosmic-ray bombardment are made, an A^{39}-A^{38} age of 0.5×10^9 years is obtained for Sikhote-Alin. The large He^3 content of the Carbo meteorite combined with its lack of A^{39} activity indicates that it must have fallen more than 2000 years ago.

Irene Fischer (Army Map Service, Washington 25, D.C.) *A Tentative World Datum from Geoidal Heights*—From all astro-geodetic material available at present geoidal heights were computed on 1927 North American Datum for the western hemisphere from Canada to

Chile, and on European Datum for the eastern hemisphere from Great Britain to Japan and from Scandinavia to South Africa. Improved reference ellipsoids were determined under various conditions for each hemisphere by the least squares method. The Columbus Geoid, gravimetrically derived by W. A. Heiskanen, was used to connect the astro-geodetic systems of the two hemispheres. By minimizing the differences between the astro-geodetic and gravimetric geoid elevations at 75 points in the western hemisphere and 127 points in the eastern hemisphere, a theoretically absolute orientation based on the Hough ellipsoid was determined, leading to a tentative World Datum. Two incidental conclusions were drawn from the map of geoid contours on the best fitting ellipsoid: triaxiality is refuted; a remarkable correlation appears between the shape of the geoid and the area of pleistocene glaciation in Fennoscandia and North America.

Robert G. Fleagle (Department of Meteorology and Climatology, University of Washington, Seattle, Wash.) *Comments on Turbulent Transfer at the Sea Surface*—Certain difficult problems are encountered in measuring temperature, humidity, and wind speed over the sea surface. A field program has been developed which minimizes these difficulties to the extent that consistent profiles in the height range between one-half and three meters have been obtained. Within this range the distributions of vapor pressure and humidity are closely logarithmic under lapse, neutral, and inversion conditions with wind speeds ranging from about two to seven meters per second.

Irving Friedman and Robert L. Smith (U.S. Geological Survey, Washington 25, D.C.) *The Hydration of Obsidian Artifacts*—The hydrated layer found on the surface of natural obsidian is thought to be the result of hydration under surficial conditions. To test this hypothesis, obsidian artifacts from dated archaeological sites were examined, and the thickness of the hydrated layer measured. Since the surfaces of the obsidian were freshly exposed by the artifact makers and then allowed to hydrate under surficial conditions, it was felt that these objects represented a controlled lab experiment stretching over many thousands of years. The artifacts were thin sectioned and the hydrated rim, which is bi-refringent and of higher index than the body of the material, was measured under the microscope. Material 500 years old (Chorrera site, Ecuador) shows a rim about one micron (±10 pct) thick; 2000 years old (Hopewell site, Ohio), 3.9 microns; 9000 years old (Danger Cave, Utah), 7.7 microns; 12,000 years old (Shalidar, Iraq), 8.9 microns; 27,500 years old (Iraq), 11.1 microns. The data fit the diffusion law $X = Dt^{1/2}$ where $D = 2 \times 10^{-18}$ cm^2/sec. The data suggest that the measurement of hydrated rims of obsidian artifacts may result in an archaeological dating method. It also proves that the hydration of obsidian under surficial conditions can be geologically important, as has been suggested by Ross and Smith and by Friedman and Smith.

Tetsuya Fujita (Department of Meteorology, University of Chicago, Chicago, Ill.) *Analysis of the Fargo Tornado of June 20, 1957*—About 40 pictures of the Fargo tornado and associated storm clouds were collected. These were taken at the time of the storm from 20 locations, which were visited afterward in order to fix their geographical positions and to obtain the direction angle of the funnel viewed from each spot. After the organization of the pictures, it became evident that the funnel dropped down from the base of a rotating cloud, two to five miles in diameter. Attention was paid to the tornado-bearing clouds which produced at least three tornadoes while moving eastward for a distance of 50 miles. The funnel of the Fargo tornado was cone-shaped until it reached maturity, and changed into a rope-like funnel in its dissipating stage. Successive changes in the shape of the storm system will be discussed in detail.

Tetsuya Fujita (Department of Meteorology, University of Chicago, Chicago, Ill.) *Precipitation and Cold-Air Production in Thunderstorm Highs*—A proposed mechanism of cold-air production caused by precipitation is presented. The study revealed that a dome of cold air was produced by the evaporation of rain drops falling beneath the cloud base. A quantitative relationship between the evaporated rain and the produced excess mass of the cold air was obtained, which revealed that the mass is proportional to the product of the amount of evaporation times a coefficient. This coefficient is a dimensionless number which varies between 1.00 and 0.00 according to the lapse rate of the atmosphere beneath the cloud base. Results of meso-analysis of squall lines and thunderstorms were used in order to estimate the actual amount of evaporation. The mass ratio of the evaporated rain to the surface rain was found to be 50–100 pct or more for a system in western Texas, but only 10 pct for a squall line in Louisiana.

Paul W. Gast (Lamont Geological Observatory, Columbia University, Palisades, N. Y.) *Isotopic Abundance of Sr^{87} in the Earth and Meteorites*—The isotopic abundance of Sr^{87} has been determined in a number of dated rocks covering a time span of almost three billion years. The initial Sr^{87} abundance was found from the age and present-day isotopic ratio. The rate of increase of this initial abundance corresponds to a Sr/Rb ratio of ten or more for the crust and upper mantle. New determinations of the strontium and rubidium content of some composite rock samples concur with a Sr/Rb ratio of about 10. The Sr/Rb ratio reported for chondrites is about three. Thus there is significant difference in the terrestrial and chondritic Sr/Rb ratio. This difference is interpreted as the result of volatilization and loss of alkali metals during the formation of the Earth.

W. Lawrence Gates (Department of Meteorology, University of California, Los Angeles, Calif.) *On the Estimation of Vertical Motion at the Tropopause*—On the basis of an earlier dynamical model assuming constant but different stability in the troposphere and stratosphere, the internal boundary conditions lead to a simple relationship for the large-scale vertical motion at a material tropopause. This relationship is analyzed in terms of typical atmospheric structure, and is applied to a synoptic example. When taken together with other dynamical estimates of mean tropospheric and mean stratospheric vertical motions, it allows an estimate of the three-dimensional vertical motion field to be made, and serves as a first approximation to the tropopause deformation.

Robert C. Gentry (National Hurricane Research Project, U.S. Weather Bureau, West Palm Beach, Fla.) *Use of Winds Inside the Strong Vertical Circulation of Hurricanes to Predict Storm Movement*—The mean resultants of winds measured by reconnaissance aircraft in each of the four quadrants of a hurricane at a single level are related to succeeding 24-hour movement of hurricanes. Resultants computed at radii varying from 30 to 100 nautical miles about the centers and at levels varying from 700 mb to 250 mb are compared with the velocity of the respective storm eyes. The relationship found in hurricanes of the 1955–1957 seasons is such as to indicate that the winds near the center of the vortex have predictive value for hurricane movement.

Bruno J. Giletti (Lamont Geological Observatory, Columbia University, Palisades, N.Y.) *Circulation Rates of Near-Surface Atlantic Ocean Waters and the Cosmic-Ray Production of Tritium*—Surface waters in the North and South Atlantic Oceans were analyzed for their tritium (H^3) concentration. The 1953 H^3:H ratio for the North Atlantic surface was 1.0×10^{-18} (eight samples). In 1954 the average increased to 1.8×10^{-18} (eight samples) as a result of thermonuclear tests. In 1956, part of the South Atlantic Surface Water averaged 0.1×10^{-18} (six samples). This shows that the increment of test debris tritium to the Southern Hemisphere was very small. Two samples indicate the influx into the South Atlantic of some tritium debris. This is under further study to establish surface mixing rates between oceans. The major parts of the North Atlantic Central Waters have a H^3:H $< 0.1 \times 10^{-18}$ (that is, a mean 'age' of $>$40 years). The upper portions of the Central Water do yield measurable H^3(H^3:H $= 0.3 \times 10^{-18}$ for three samples). Based on the above surface data it is possible to calculate the influx rate of tritium into the North Atlantic Surface Water and therefore find the cosmic-ray production rate of tritium. The new South Atlantic data require an influx of 1.4 H^3 atoms/cm^2 sec into the North Atlantic. Taking residence times for tritium in the atmosphere into account, calculations yield a total production rate of 1.8 H^3 atoms/cm^2 sec.

Thomas A. Gleeson (Department of Meteorology, Florida State University, Tallahassee, Fla.) *Probability of Observing Specific Phenomena from Network Stations*—The probability that an atmospheric feature of a given size will be observed in a region with a network of stations randomly distributed relative to the feature is shown to be a function of the feature size and the density of the network. The latter is defined as the number of stations divided by the size of the region. The function is developed to give the probability of observing several features simultaneously in a network of stations with varying observational capabilities. Applications to network design, climatology, and prediction are discussed, and effects of a variation in network density are considered.

T. Gold and D. H. Menzel (Harvard College Observatory, Cambridge, Mass.) *A New Method of Obtaining Seismic Information*—The artificial generation of usable seismic signals has so far been achieved only with explosions. The present proposal is to use an oscillatory signal transmitted into the ground by a special mechanical generator, and to receive the signal at one or many places with a receiver using a new phase-sensitive integrating technique. The great discrimination against random disturbances and noise enables this technique to achieve a sensitivity equivalent to an increase by a factor of several thousand in the transmitting power. Variations of the reception pattern with frequency give significant information about the sub-surface structure. Feasible transmitter designs indicate the possibility of attaining very great ranges. Measurements of attenuation, seismic path-length, and other characteristics can be carried out. A large installation working on this principle may send a signal to the antipodes.

S. S. Goldich, A. O. Nier, and H. Baadsgaard (University of Minnesota, Minneapolis, Minn.) *Three-fold Division of Precambrian in the Lake Superior Region*—K-A dating supports the three-fold division of the Precambrian of Minnesota and adjacent areas. The three divisions from dating of major orogenies and unconformities are early Precambrian (older than 2.5 b y), Middle Precambrian (2.5–1.6 b y), and late Precambrian (1.6–0.5 b y). The major orogeny at the end of early Precambrian time is dated by numerous samples from Ontario, northern Minnesota, and the Minnesota River Valley. A second major folding marks the close of the Middle Precambrian and involved Animikian sediments in Minnesota, Wisconsin, and Michigan. Geologic time since 1.6 b y is assigned to the late Precambrian. Keweenawan lavas and the Duluth gabbro complex are assigned to the Middle Keweenawan. The main gabbro intrusion is dated at 1.1 b y, but folding and metamorphism of the extent developed at this time in the Grenville Province still remain to be recognized in the Lake Superior region.

S. S. Goldich, A. O. Nier, H. W. Krueger, and J. H. Hoffman (University of Minnesota, Minneapolis, Minn.) *K-A Dating of Precambrian Iron Formations*—K-A dating indicates that iron formations were involved in each of the major orogenies of the Canadian Shield. Soudan-type of iron formations in Minnesota and Ontario were folded in a 2.7–2.5 b y orogeny. Mesabi-type of iron formations in Minnesota, Wisconsin, and Michigan were involved in folding at 1.8–1.6 b y, and iron formations in Quebec (Ungava-type) were folded in the 1.2–1.0 b y or Grenville orogeny as indicated by samples from the Jeanine Lake and Mt. Reed deposits. Sericite samples from the Soudan Mine, Minnesota, date two periods of mineralization. The older sericite (2.5 b y) is related to folding at the end of early Precambrian time. The younger sericite (1.7 b y) indicates that the deposits were reopened at the time of the Middle Precambrian (post-Animikian) orogeny. Geologic data indicate that iron formations probably were deposited at different times within each of the main divisions of the Precambrian. Further studies are needed.

D. T. Griggs, H. C. Heard (University of California, Los Angeles 24, Calif.), F. J. Turner (University of California, Berkeley 4, Calif.), and M. S. Paterson (Australian National University, Canberra, Australia) *Recrystallization in Calcite Crystals and Aggregates*—Yule marble highly strained at 600°C, 5 kb confining pressure, exhibits partial syntectonic recrystallization. The new crystals are highly oriented, with the c axis parallel to the maximum compressive stress, consistent with G. J. F. MacDonald's revised thermodynamic theory. When strained at 700° and 800°C, 5 kb, the recrystallization is markedly less evident. Annealing experiments similar to those of Buerger and Washken were performed at high pressure. The sample is first strained at room temperature under a high confining pressure. The shear stress is then removed and the sample is heated at pressure. Development of a completely recrystallized granoblastic texture with polygonal grain outlines will be illustrated. Porphyroblastic texture will also be shown. The critical temperature for annealing recrystallization of yule marble strained 20 pct at 5 kb is about 500°C. The recrystallized grains in annealed samples are less well oriented than the unrecrystallized fabric. Single crystals of calcite exhibit annealing recrystallization when deformed by either twinning or translation. The recrystallized segments of these grains are commonly oriented with the c axis inclined 25–30° to that of the host. Internally rotated e lamellae and r cleavages frequently act as barriers to new growth and so tend to form boundaries of new crystals. Recrystallization of calcite is similar in every way yet explored to recrystallization of metals. Water and CO_2 do not affect the process in our experience to date.

Irving I. Gringorton (Atmospheric Analysis Laboratory, Geophysics Research Directorate, Air Force Cambridge Research Center, Boston, Mass.) *Equivalent Tailwind Errors of Forecast and Inflight Observation*—In the daily routine of transoceanic flying figures are collected which yield forecast wind factors and observed wind factors from which it is possible to obtain a partial, but adequate, separation of errors. The analysis can provide useful information for the evaluation of the wind forecasts. Coupled with this evaluation a technique is presented for the verification of upper-air prognostic charts.

Donald W. Groff (Department of Geology' Allegheny College, Meadville, Pa.) *A Graphic Approach to Meaningful Radiometry*—A reasonably precise rapid counting technique permitting variable sample weights has been developed. With the use of a nomogram the results may be translated to a common scale giving per cent equivalent uranium. Fifteen samples of known 'uranium equivalent' were exposed beneath a Geiger tube and the results plotted; counts per minute vs sample weights. The graphed curves appear a family of parabolas. Log-log plots indicate a linear relationship with an average slope of +0.4. The maximum standard error of estimate for any individual regression was +0.3 unit and the total correlation coefficient was found to be 0.79.

H. P. Guy (Quality of Water Branch, Water Resources Division, U.S. Geological Survey, Washington 25, D.C.) *A Method for Determining Trend of Suspended-Sediment Discharge in Streams*—The trend of discharge of suspended sediment by streams is evaluated by a graphical method, using measured factors for a storm, including rainfall intensity, quantity and rate of runoff, and season. The method is illustrated by using sediment discharge, water discharge, and precipitation data for the Brandywine Creek at Wilmington, Del., during the period 1947 to 1955. Runoff and sediment data for 123 storm periods representing 89 pct of the total sediment discharge and 19 pct of the total water discharge were used in the analysis. A 38 pct reduction in sediment yield occurred from the first half to the last half of the nine-year period. The relative significance of the trend is shown by a rank-correlation method, and for these data the downward trend is highly significant.

William H. Haggard (Office of Climatology, U.S. Weather Bureau, Washington, D.C.) *The Birthplace of North Atlantic Tropical Storms*—Seventy-one years of North Atlantic tropical storms and hurricanes have been investigated in the Office of Climatology of the U.S. Weather Bureau. The reconstructed storm-track charts were used to investigate the birthplace of North Atlantic tropical storms. The results are discussed in the light of the inadequacies of the observing net. Examples are given of storms whose origins have been especially investigated. Suggestions are offered for improvement of methods for earlier storm detection.

John Handin (Shell Development Co., Houston 25, Texas) *Effects of Temperature on the Strengths of Some Sedimentary Rocks*—Jacketed dry specimens of anhydrite, two dolomite rocks, three limestones, two sandstones, shale, siltstone, and slate, as well as halite crystals, have been tested in triaxial compression at a strain rate of one per cent per minute under confining pressures of 0–2000 bars and at temperatures of 24–300°C. The experimental conditions simulate depths to 30,000 feet. Heating under a given confining pressure can reduce the ultimate strength by lowering the yield stress or decreasing strain-hardening or both. An increase of temperature enhances ductility in all but one dolomite, the shale, and the siltstone. In these a reduction of ductility results in a lowered ultimate strength. Heating can increase strength by enhancing ductility in work-hardening materials, provided that the yield stress is not too greatly decreased. For all materials tested, except the halite, the ultimate strength at any simulated depth exceeds the crushing strength at atmospheric conditions.

G. E. Harbeck and G. E. Koberg (Water Resources Division, U.S. Geological Survey, Denver, Colo.) *A Method of Evaluating Effects of a Monomolecular Film in Suppressing Reservoir Evaporation*—Evaporation from a water surface may be reduced by the application of a monomolecular film. Errors may be introduced in the computed savings if pan measurements are used. Experiments show that evaporation pan coefficients vary with the season, and the coefficients cannot be evaluated accurately. A more reliable measure of the evaporation reduction is obtained by the solution of simultaneous equations based upon energy budget and mass transfer theory. The rise in water surface temperature caused by application of the film can be computed.

HARRY F. HAWKINS (National Hurricane Research Project, U.S. Weather Bureau, West Palm Beach, Fla.) *Hurricane Winds at Flight Levels Related to Low-Level Wind Data*—Flight data collected at the National Hurricane Research Project is supplemented where practical by other reports to afford an empirical relationship enabling the forecaster to estimate the distribution of winds near the surface in hurricanes when given only flight level reports from the 700-mb or higher levels. Stage of growth of the hurricane, general intensity of circulation, and sector of the storm are considered where possible in treating the vertical wind profile.

HUGH C. HEARD (Institute of Geophysics, University of California, Los Angeles 24, Calif.) *The Brittle to Ductile Transition in Solenhofen Limestone as a Function of Temperature, Confining Pressure, and Interstitial Fluid Pressure*—One hundred and fifteen triaxial compression and extension experiments have been performed on the mechanically isotropic homogeneous Solenhofen limestone to determine the transition from brittle fracture to ductile flow as a function of temperature, confining pressure, and interstitial fluid pressure. Temperatures and pressures range from 25°–700°C and from 1–7500 atmospheres; interstitial fluids include water and carbon dioxide. Strain rates remained constant at 10^{-4}/second. Transitional behavior is arbitrarily defined as that point at which three to five per cent strain may be induced without notable loss in cohesion. In dry extension tests, the confining pressure required to induce transitional behavior decreases from 7300 atmospheres at 25°C to about 700 atmospheres at 700°C. In dry compression tests, the pressure required for the transition is 1000 atmospheres at 25°C, decreasing to one atmosphere at 480°C. For transitional behavior in compression tests with interstitial fluids, the difference between confining pressure and interstitial pressure decreased almost exponentially with increasing confining pressure from 1000 atmospheres at 25°C and 850 atmospheres at 150°C to nearly zero at 5000 atmospheres. Sample stress-strain data are presented and compared for a wide range of test conditions. From plots relating transition pressure and transition stress to temperature, maximum and minimum principal stresses and mean stress are derived and reported as a function of temperature. None of the various theories of strength examined were able to correlate results in compression and extension. The Mohr theory was able to predict shear fracture angles at the brittle-ductile transition within 0°–6° for dry compression and 3°–10° for extension at temperatures ranging from 25°–400°C. Fracture angles (to the least principal stress axis) were found to increase with temperature in all cases.

W. A. HEISKANEN AND U. A. UOTILA (Ohio State University, Columbus, Ohio) *On the Accuracy of the Gravimetric N, ξ, and η*—The determination of the vertical deflection components ξ and η and of the undulation N of the geoid is the most important geodetic problem of this decade. When we know N, ξ, and η, we know also the detailed shape of the geoid and its distance from the reference ellipsoid, and we can convert the existing geodetic systems, also across the oceans, to the world geodetic system. Most effectively N, ξ, and η can be determined by the gravimetric method. The authors discuss the following problems: what kind of gravity field is required to get the highest possible accuracy; for what areas the additional gravity observations are mostly needed; what accuracy can be obtained on basis of the existing gravity material; how we can best choose the computation points; how to estimate the gravity anomalies for the unsurveyed areas; what accuracy can we expect in converting the geodetic systems across the oceans; and what accuracy has been, in fact, obtained in the studies of the Columbus group.

HOMER W. HISER (Marine Laboratory, University of Miami, Coral Gables, Fla.) *Anomalous Radar Propagation in South Florida*—Data are presented which indicate that the amount of anomalous propagation observed under given atmospheric conditions is partially a function of radar wave length. Case studies of rapid time variations and marked areal differences in the distribution of anomalous propagation are also presented.

WALTER H. HOECKER, JR. (Office of Meteorological Research, U.S. Weather Bureau, Washington, D.C.) *Comparison of Dimensional and Time-Trend Characteristics of Some Tornadoes and Waterspouts*—Utilizing scale serial photographs of tornadoes, the size and shape trends of several tornadoes (1955–1957) are presented. These are compared to other measurements of tornadoes and waterspouts which occurred between the years of 1896 and 1955. Relationships have been found between width and height of those tornadoes where serial photographs are available and the findings are summarized.

JOHN H. HOFFMAN AND ALFRED O. NIER (University of Minnesota, Minneapolis 14, Minn.) *Cosmogenic Helium Distribution in Iron Meteorites*—Among the evaporation products formed when cosmic rays interact with the nuclei of matter, for example, iron, are He^3 and He^4. The quantity formed of both these isotopes should be a function of their position in a large meteorite mass. A mass spectrometer investigation of the He^3 and He^4 contents in cross sections of the half-ton iron meteorites Carbo and Grant shows a monotonic decrease toward the interior. Whereas the He^3/He^4 ratio in Carbo is approximately constant at 0.24 throughout the meteorite, it decreases monotonically from 0.30 to 0.26 between the surface and center of Grant. Contours of constant He^3 concentrations suggest that Carbo was split at a time recent compared with that required for cosmic rays to generate the He^3 found. The results are compared with computations assuming an omnidirectional cosmic-ray flux interacting with regular-shaped bodies of various sizes.

Marvin D. Hoover (U.S. Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, Colo.) *Vegetation and Land-Use Effects*—The role of forest and range vegetation in determining streamflow and soil stability is discussed. The limits to possible effects of plant cover changes as controlled by climate, soils, and other factors are considered. Present knowledge is appraised, additional research needs indicated, and suggestions made for future investigations. It is now evident that in certain areas quantity of streamflow is related to plant cover, although it is uncertain how widely results can be applied because of incomplete knowledge. Energy-balance method and other contributions of physicists are helpful. Difficulty in direct measurements may lead to dependence on misleading assumptions. More attention must be given to biological aspects and to differences in water use between plant species. Physical, chemical, and bacteriological quality of water are of concern and deserve greater emphasis in future studies of land-use effects. There are still many questions concerning most efficient plants and management measures to reduce sheet and gully erosion, as well as the relation between plant cover and landslides and other mass movements.

Charles L. Hosler (Pennsylvania State University, University Park, Pa.) *The Role of Dilute Solutions in Nucleating the Ice Phase*—A number of experiments are now complete which demonstrate that a number of soluble salts in extremely small concentrations have a profound effect on the freezing temperature of water. These experiments will be discussed and compared. The conclusion is reached that ions in solution provide an additional manner in which the freezing temperature of water can be elevated.

Floyd W. Hough (2412 N. Columbus St., Arlington 7, Va.) *The Role of the Geodesist*—The contribution of geodesy to the scientific progress of the world is not too apparent to the layman or, perhaps, even to other branches of the geophysical sciences. An attempt is made in this paper to present a portion of the impact of the geodesist upon the civilization of the planet during a historical period of more than two thousand years with a brief preview of its essentialness in the new age.

L. F. Hubert (Office of Meteorological Research, U.S. Weather Bureau, Washington, D.C.) *Distribution of Surface Friction in Hurricanes*—Terms of the horizontal equations of motion are evaluated from the surface data of three hurricanes that entered our southeastern coast, to investigate the magnitude and orientation of the friction vector at anemometer level, and to compare it with non-hurricane situations. While the magnitude of friction increased toward the hurricane center, it is demonstrated that it is not a simple function of wind speed. Furthermore, the component of friction normal to the anemometer wind direction is nearly always significant and in many cases exceeds the tangential component. The implication of these results are mentioned from the viewpoint of the classical definition of wind stress and its variation with height.

F. A. Huff and J. C. Neill (Illinois State Water Survey, Urbana, Ill.) *Application of Several Statistical Methods to Rainfall Frequency Analysis*—Several methods of frequency analysis were investigated using annual and seasonal maxima for 1- to 10-day storm periods in Illinois. Analysis was based upon data from 39 stations for a 40-year period. Several commonly used statistical distributions, such as the Gumbel and log probability laws, were compared for goodness of fit. Differences obtained in data fitting by application of the methods of moments and least squares were investigated. Consideration was given to both individual station analysis and to grouping of station data within meteorologically homogeneous areas for derivation of the Illinois frequency relations. Final relations were determined using the areal approach in which the state was divided into four sections having similar storm characteristics. Confidence limit computations were made to define the range of variability about the areal mean frequency curves.

C. E. Jacob (Box 347, Northridge, Calif.) *Salt-Water Encroachment in Inclined Confined Aquifers of Nonuniform Thickness*—This is a generalization of an earlier paper on uniform horizontal aquifers. By the method of Dupuit, simultaneous partial differential equations are obtained for the salt-water flow and the fresh-water flow. Integrations are possible in certain cases of steady flow, both opposed and parallel. Nonsteady states are treated by graphical integration between successive steady states or uniformly varying states. Simultaneous finite-difference equations are set up for numerical integration or solution by electronic analog. The long-term time characteristics of such systems are considered, also the lagging of the encroachment behind the lowering of head landward from the salt water lens. Tidal phenomena, diffusion, and rinsing are also discussed.

W. S. Jardetzky (Lamont Geological Observatory, Columbia University, Palisades, N.Y.) *On a Direct Representation of a Disturbance in an Elastic Medium*—The expressions for displacements derived by Ostrogradsky (1831) directly from the equations of motion are presented in a slightly generalized form. This solution has a very important form for the interpretation of propagation of a disturbance in an elastic medium from a limited region in the latter. It appears that the disturbance at every point of an unlimited medium results from the superposition of effects propagating from that region with velocities ranging from the velocity of compressional waves to that of the shear waves, in accordance with a similar conclusion reached by Love.

R. Jastrow and I. Harris (U. S. Naval Research Laboratory, Washington, D. C.) *Upper Atmosphere Properties from Minitrack Observations on 1957 $\alpha 2$*—The analysis of Minitrack data on the first U.S.S.R. satellite, 1957 $\alpha 2$, provides information on the density and temperature of the atmosphere above the perigee altitude of 232 km. The combination of the $\alpha 2$ data with recently obtained rocket data at altitudes below 200 km leads to a relatively unambiguous determination of density up to 400 km. We find that at 275 km the density is 1.4×10^{-13} g/cm^3 or 13 times the ARDC density, with an uncertainty of 30 pct; at 400 km the density is 2×10^{-14} g/cm^3 or 40 times the ARDC density, with an uncertainty of a factor of 2; and at 800 km the density is 10^{-16} g/cm^3 or 100 times ARDC density, with an uncertainty of a factor of 5. Upper atmosphere temperatures appear to be higher than those in earlier models. At 250 km the temperature is found to be 1600° ± 400° K, as compared with 900° K in the ARDC model. The lifetimes for existing satellites, as determined by our model, are as follows: 1958 α, minimum one year, probable value two years; 1958 β, 80 to 400 years; 1958 γ, minimum 70 days, probable value 140 days. The minimum values quoted for 1958 α and 1958 γ are based on the assumption of a 90° angle of attack at perigee. The range given for the lifetime of 1958 β corresponds to the probable error in density of our model at the perigee altitude of that satellite.

K. R. Johannessen (Directorate of Scientific Services, Air Weather Service, Andrews Air Force Base, Washington, D.C.) *Some Studies of 'Weather' as an Initial Value Problem*—The effects of inadequate definition of the initial values may be studied systematically when a mathematical prediction model exists for the problem. Such effects have been studied by Thompson, Best, and others for the problem of large-scale flow prediction. Successful predictions of 'weather'; that is, fog, clouds, precipitation, visibility, etc., require ideally an extremely complex set of initial values, among them the parameters currently used in large-scale predictions of flow. In this connection forecasters are often faced with the question: What is the minimum amount of data which will permit operationally useful forecasts of 'weather'? This paper reports on results of applying varying types and amounts of data towards the problem of predicting cloud at mid-tropospheric levels, including those characterizing the large-scale flow.

R. K. C. Johns (Laboratory for Electronics, Inc., Boston 14, Mass.) *Adjustment of Conditioned Observations with Unknowns*—A method of adjustment with two kinds of unknowns is developed. Some unknowns are directly observed, the others are indirectly determined from the observations. In the described method fictitious observation equations with corresponding weights are introduced and equivalent normal equations formed. An application for simultaneous determination in geodetic astronomy is given.

C. Y. Johnson, E. B. Meadows, and J. C. Holmes (U. S. Naval Research Laboratory, Washington 25, D. C.) *Ion Composition of the Arctic Ionosphere*—Three Aerobee-Hi rockets identically instrumented with Bennett radio frequency ion mass spectrometers were launched from Fort Churchill, Canada, on November 20, 1956, February 21, 1958, and March 23, 1958; their peak altitudes were 251, 225 and 202 km respectively. The November flight was at night into an overcast which prevented observation of the overhead sky. The February flight was at night and entered an auroral display. The March flight was at noontime. Positive and negative ions were detected on all flights. Masses 32^+ (O_2^+), 30^+ (NO^+), and 16^+ (O^+) AMU were the major positive ions detected. An ion in the region of mass 46^- (NO_2^-) was the negative ion detected. Mass 30^+ (NO^+) is the predominant positive ion at night below 200 km, but during the day is supplanted by 32^+ (O_2^+) below 100 km, and by 16^+ (O^+) above 150 km. Mass 16^+ (O^+) does not appear below 130 km, but becomes the predominant ion above 200 km on all flights. In addition, small amounts of 28^+ (N_2^+), 18^+ (H_2O^+ ?), and 14^+ (N^+) AMU were detected on all flights. An important feature of the February 1958 data is the approximately equal abundance of ions 32^+ (O_2^+), 30^+ (NO^+) and 28^+ (N_2^+) AMU which occurred in the 100–105 km. region of an auroral display.

C. L. Jordan (Florida State University, Tallahassee, Fla.) *The Thermal Structure of the Hurricane Core*—Many aircraft and dropsonde observations have been made in and near the eye of hurricanes in recent years. The dropsonde observations have enabled the preparation of mean eye soundings for hurricanes of various intensities, and the aircraft observations provide information on the horizontal temperature gradients in and near the eye. The three-dimensional temperature distribution in the hurricane core, as derived from these observations, is discussed along with the vertical circulation patterns which have been postulated for this portion of the hurricane.

Donald L. Jorgensen (Forecasts and Synoptic Reports Division, U.S. Weather Bureau, Washington, D.C.) *Predicting Atlantic Coast Hurricanes by Means of Synoptic-Climatological Relationships Using Orthogonal Polynomials*—The Wadsworth-Bryan method of specifying atmospheric circulation patterns is used as a basis for developing a hurricane forecasting procedure. Regression equations have been calculated using persistency and circulation parameters to give 24-hour components of motion for hurricanes threatening the middle and north Atlantic coast areas. The final forecast is expressed in terms of probability areas.

Paul Julian, William R. Larue, and Hans Panofsky (Pennsylvania State University, University Park, Pa.) *Estimation of 100-mb Flow from 500-mb Space Smoothed Charts*—The contour pattern in moderate latitudes at 100-mb resembles 500-mb patterns with the short waves smoothed out. It is shown that space-smoothed 500-mb charts can be used satisfactorily to estimate 100-mb contour patterns and winds. Even in polar regions, changes in the mean flow at 500-mb are shown to be well correlated with changes at 100-mb.

Christian E. Junge (Geophysics Research Directorate, Air Force Cambridge Research Center, Bedford, Mass.) *The Sulfur Budget in the Atmosphere*—On the basis of rainwater analyses data, estimates on the global budget of the sulfur are given. It appears that about 30 pct of the sulfur can be accounted for by human activities. Analyses of ice samples from Greenland back to the year 1915 will be used to check this result. A review of the facts and problems of the sulfur cycle in the atmosphere will close the considerations.

K. Kajiura (Department of Oceanography and Meteorology, A and M College of Texas, College Station, Texas) *Effect of Coriolis Force on Edge Waves: II, Specific Examples of Free and Forced Waves*—The modification of edge waves due to the presence of the Coriolis force is examined in terms of two specific problems. In particular, the dispersion of an initial deformation of the water surface and the forced wave due to a moving atmospheric pressure disturbance are discussed. In both cases, the scale of the disturbance is an important factor and the larger the scale, the larger is the effect of the Coriolis force. In the northern hemisphere the initial deformation of the water surface is split into two free edge waves in which the wave moving to the left facing the coast from the sea side has a larger amplitude than the wave moving to the right. The contribution of the Coriolis force to the edge-wave amplitude for an initial deformation of several hundred kilometers is about 20 pct at the center in the initial stage. In the case of forced waves, the movement of the atmospheric pressure system to the left is more favorable for exciting resurgent edge waves than the movement to the right. The contribution of the Coriolis force is about 10 to 20 pct in the amplitude of the edge waves if the atmospheric disturbance of several hundred kilometers in diameter moves to the left with a speed of about 20 to 30 knots.

Akira Kasahara (Department of Meteorology, University of Chicago, Chicago, Ill.) *A Comparison between Geostrophic and Quasi-Nongeostrophic Numerical Forecasts of Hurricane Movement with the Steering Model*—The steering flow of a hurricane is obtained by eliminating the vortex field from the total flow field. The evolution of the steering flow is predicted by solving the barotropic nondivergent vorticity equation. Based upon the steering-flow prediction, a forecast of the hurricane movement is obtained with the use of an equation which provides for interaction between the hurricane and the steering flow. In the geostrophic steering model, the geostrophic-wind assumption is used for convenience in solving the vorticity equation. In the quasi-neogeostrophic steering model, this assumption is discarded and the stream function governed by the 'balance equation' is adopted as a parameter for solving the vorticity equation.

With the above two models, a total of 94 predictions of the 24-hour and 48-hour movement of hurricanes Diane, Connie (August 1955), and Betsy (August 1956) at the 500- and 700-mb levels were prepared by the use of an electronic computer. A detailed discussion of the above results is presented. Generally speaking, the performance of the quasi-nongeostrophic steering model indicates a tendency to improve the accuracy of the hurricane movement forecast in comparison with that of the geostrophic steering model.

W. M. Kaula (Army Map Service, Washington 25, D.C.) *A Statistical and Harmonic Analysis of Gravity*—Stochastic process methods have been adapted to analyze gravity using spherical harmonics in place of the customary Fourier functions. Transition matrices and autocovariances of free air anomalies were computed from a world sample of 749 observations (of average spacing 500 km), eight regional samples (100 km), and nine local samples (15 km). These samples were divided into various sub-samples in order to obtain either balance with respect to regional topography or smoothing out of local topography.

From the autocovariances can be obtained the variance, or power, of each harmonic degree of gravity. These variances are usable in turn for: (1) the variances and covariances of geoid heights and deflections of the vertical; (2) conditions on the magnitudes of the degrees in direct harmonic analysis of gravity; (3) errors of representation of gravity observations; and (4) the variances and autocovariances of the gravitational field at any altitude, from which a statistical estimate can be made of satellite perturbations.

Gilbert D. Kinzer and W. E. Cobb (Office of Physical Research, U.S. Weather Bureau, Washington, D.C.) *Analysis of the Growth and Collection Efficiency of Cloud Droplets*—Experimental collection efficiencies obtained from the data agree within limits of experimental error with those calculated from a theory that is developed from intuitive physical arguments which are based on a superimposed random motion observed in the fall of droplets in the supporting cloud. The theory implies that a small-scale eddy diffusion transfers smaller droplets from the parent cloud to the growing droplet. The coefficient of droplet transport calculated from the theory agrees well with one evaluated experimentally.

Carl Kisslinger (St. Louis University, St. Louis, Mo.) *Observations of the Development of the Surface Wave Pattern in the Vicinity of Small Explosions*—Displacements at the surface of a relatively simple layered system have been recorded at distances from 25 to 700 ft from a number of small explosions by means of three-component mechanical-optical seismographs. The characteristics of the surface waves generated have been determined as the first step in a further study of the factors governing these characteristics. Two seismic models are represented by the field conditions. Excellent reproducibility of recorded motion was obtained from repeated shots under similar circumstances. From a study of the particle motion diagrams in the vertical-longitudinal plane, distinct wave types, well separated at the larger distances, can be followed back to their rudimentary form at the smaller distances. The Rayleigh wave in both models is not strongly dispersed, but consists of a single large ellipse, followed by a brief train of shorter period waves of much smaller amplitude. This train does not lengthen appreciably with distance. In one model, the Rayleigh wave is preceded by well-defined direct elliptic motion of shorter period. This motion develops into two successive trains, in each of which the period decreases slightly with time. Differences in the complexity of the recorded motion in the two models is noted.

Melvin H. Kleen and William H. Sammons (Central Technical Unit, Soil Conservation Service, Beltsville, Maryland) *Agricultural Watershed Influences on Runoff Potential*—Annual and seasonal precipitation and runoff data for selected agricultural watersheds in the United States were analyzed statistically for relationships pertinent to the watershed program of the Soil Conservation Service. Records in the Monthly

Precipitation and Runoff for Small Agricultural Watersheds in the United States as published by U. S. Department of Agriculture, Agricultural Research Service, Soil and Water Conservation Research Branch, were considered. A water year, growing season, and dormant season for the selected watershed were based on Figure 90, Average Dates of Last Killing Frost in Spring, and Figure 107, Average Dates of First Killing Frost in Fall, in the section on *Climate-Frost and the Growing Season* of the *Atlas of Americn Agriculture* (1936). Watersheds were variable in area, climate, slopes, soils, flow character, cover conditions, etc. The study was centered about the relationship $(P - Q)/S = Q/P$, where P is the precipitation in inches, Q is the runoff in inches, and S is the maximum potential difference between P and Q for the period, in inches. $(P - Q)/S$ is visualized as the ratio of actual to potential difference between P and Q, and Q/P is visualized as the ratio of actual to potential runoff. Under this hypothesis, the data were studied and recommendations and conclusions presented.

L. Knopoff, J. F. Gilbert, and W. L. Pilant (University of California, Los Angeles, Calif.) *Pulse Propagation in a Medium with a Single Layer*—The generation of Love SH-waves has already been studied. In a similar way the propagation of *P-SV* motions in a layered medium can be represented as the sum of contributions from an infinite set of images of the source taken in the two boundaries. The train of Rayleigh waves is seen to lengthen as the epicentral distance increases. The other important pulse groups are the refracted P and S events; each of these lengthens with increase in epicentral distance. A seismic model has been set up to demonstrate these features; the details predicted above are observed with high fidelity. The long duration and the modulation envelopes of the refracted P and S events are features not heretofore anticipated, but whose existence have since been verified theoretically. A new experimental technique for directly determining the group velocity in layered structures is presented and the results for the seismic model with one surface layer agree with the theoretical values.

Leon Knopoff (University of California, Los Angeles, Calif.) and Gordon J. F. MacDonald (Massachusetts Institute of Technology, Cambridge, Mass.) *The Magnetic Field and the Central Core of the Earth*—The suggestion that the inner core of the Earth is liquid and is the seat of a strong magnetic field is examined. Contrary to expectations of a magnetohydrodynamic rigidity for the inner core, a liquid inner core with a strong magnetic field should not transmit shear waves. The absence of the phase *PKJKP* in seismic records is favorable to the hypothesis of a strong magnetic field in a liquid inner core. If the jump in P-wave velocity at the inner core boundary is due to a magnetic field, the strength of the field must be of the order of 5×10^6 gauss whether the field geometry is toroidal or random. A strong toroidal field leads to a seismic ellipticity of the inner core. No such ellipticity is observed. Hence if the field in the inner core is toroidal, it must be less than 5×10^5 gauss. A random field does not lead to an ellipticity and the limit on the magnitude of a random field is determined from seismic velocities. A difference in iron-nickel to silicon ratio between the outer and inner core is suggested as leading to a discontinuity in conductivity whereby a strong field could be stored in the inner core. Consequences of the liquid inner core model include (1) a central temperature in excess of 4000°K and (2) a magnetic time constant of about 5000 years.

Adam Kochanski (Headquarters, Air Weather Service, Andrews Air Force Base, Washington, D.C.) *Route Winds for Flights at 300 and 200 mb*—Commercial jet airliners operating near the level of maximum wind will create a new problem. Critical values in fuel reserve and in errors of wind forecasts will have to be considered on a routine, day-to-day basis. This paper discusses our present capability of forecasting route winds at 300 and 200 mb. Vector errors and tail-component errors of 36-hour and 48-hour route winds were evaluated using prognostic and verifying charts. Estimates of errors of 12-hour and 24-hour forecasts are also given. In general, the errors decrease steadily with increasing route length and the rate of this decrease seems to be nearly constant for most of the middle latitudes and for 24-, 36-, and 48-hour forecasts.

J. Laurence Kulp and L. E. Long (Lamont Geological Observatory, Columbia University, Palisades, N. Y.) *Chronology of Major Metamorphic Events in Southeastern United States*—Absolute age measurements by the potassium-argon, rubidium-strontium, and uranium-lead methods on rocks from New York to Georgia suggest that the major metamorphic event occurred about 360 m y ago. This orogeny produced the homogeneous granites of the Piedmont (previously called '*Carboniferous*') and either formed or recrystallized the gneisses and schists. Thus, rocks that may be Grenville in age, for example, Fordham gneiss, Baltimore gneiss, and Carolina gneiss and schist give approximately the same apparent age by the potassium-argon method as the rocks that may be post-Cambrian, for example, Inwood marble, Gaffney marble, Wissahickon schist, and Manhattan schist. In western North Carolina a transition of apparent ages from 360 to 800 m y occurs in the same rock unit sharing the margin of the 360 m y event. In the southeastern Piedmont of Georgia there is evidence for a younger event occurring around 260 m y ago.

M. Landisman and Y. Sato (Lamont Geological Observatory, Palisades, N. Y.) *Shear Wave Velocities in the Upper Mantle*—A period equation has been developed for Love waves in models having two homogeneous layers over a half space with linear gradients in both density and shear modulus. The dispersion for various theoretical models of this class was compared with observations of Love wave group velocity for periods from 20 to 300 sec. Shear wave travel times for spherical Earth models having these velocity structures were compared with observations from earthquakes. It is concluded that a knowledge of the exact structure of the crust is not necessary for an investigation of the shear velocity in the upper mantle, while crustal investigations do require some knowledge of mantle structure. The only shear velocity structures which are concordant with observations of surface wave dispersion and body wave travel times are those containing a low velocity layer in the region from roughly 100 to 200 km below the Earth's surface. Further studies to define the structure of this low velocity channel are in progress.

W. B. Langbein (U.S. Geological Survey, Washington 25, D.C.) *Basic Hydrologic Data for Upstream Engineering and Land Management*—Land use is water use, and erosion control means water control. These are the basic precepts of upstream engineering and land management. Hydrologic data therefore are at the core of any plans for these purposes. But far more detailed knowledge is needed than now exists. The extensive programs for upstream watershed practice and land management are guided by sound but generalized data. The available information is not nearly detailed enough to provide answers to the almost infinite variety of field conditions which are encountered.

N. E. Laseur (Department of Meteorology, Florida State University, Tallahassee, Fla.) *Detailed Low-Level Wind and Pressure Data from Hurricane Edith, 1955*—Special aircraft reconnaissance flights on four consecutive days, August 27–30, 1955, into Hurricane Edith, yield data which permit quite detailed analysis of low-level (1000 to 1500 ft) wind and pressure fields. A description of the micro-structure revealed by these analyses will be presented together with a discussion of relationships with cloud and weather patterns.

A. W. Lawson and John C. Jamieson (University of Chicago, Chicago 37, Ill.) *Energy Transfer in the Earth's Mantle*—Several processes of energy transfer in the Earth's mantle are examined: (1) grey radiation, (2) ambipolar diffusion of electron-hole pairs, (3) exciton transfer, and others. Using Rikitake's values of the electrical conductivity, corrected for the infrequency dependence and the refractive index variation with depth, the values for the radiative contribution to the heat flow were found to be appreciably larger than those estimated by Clark. Estimation of the electronic processes indicate that they may be an important component of the heat flow in the lower parts of the mantle. All processes considered tend to increase the heat conductivity of the mantle and thereby presumably lower the estimate of the temperature at the base of the mantle.

Dale F. Leipper (Department of Oceanography and Meteorology, A and M College of Texas, College Station, Texas) *The Impact on Oceanography of the NAS Meteorology Report*—The Committee on Meteorology of the National Academy of Sciences-National Research Council submitted an interim report in January 1958 on Research and Education in Meteorology. Although this report concerns the history, present status, and future of meteorology, it carries with it considerable implications for the field of oceanography. These will be discussed.

Dale F. Leipper (Department of Oceanography and Meteorology, A and M College of Texas, College Station, Texas) *Staff and New Facilities in Oceanography at Texas A and M*—The Department of Oceanography and Meteorology, A and M College of Texas, has obtained a building on the beach at Galveston for the purpose of enlarging its marine laboratory there. K. M. Rae has been named Director of Marine Laboratory Programs with offices in College Station, and Albert Collier is Chief Scientist of the Galveston Marine Laboratory. The Texas A and M Research Foundation has obtained the 126-ft *Hidalgo*, former PCS, and the 56-ft motor sailer *Elena* for use in oceanographic research. The former is participating in the program for the IGY. J. R. Lumby has been named associate director of the IGY Oceanographic Archive. On the campus, the digital computer laboratory and Nuclear Science Centers are developing rapidly.

Edward N. Lorenz (Department of Meteorology, Massachusetts Institute of Technology, Cambridge, Mass.) *Non-Linear versus Linear Objective Weather Predictions*—A prediction formula is called linear if an observable predictand is expressed as a linear combination of present and past observable predictors. Most of the recently established empirical prediction formulas are linear. An artificial series of 'weather maps' is constructed in which the best predictions of future displacements of pressure systems are linear functions of past displacements. The corresponding formulas for future pressures in terms of present and past pressures are nonlinear. The reduction of variance obtained in predicting pressure by these nonlinear formulas cannot be duplicated by the best linear approximations to them. This situation still prevails when 'observational' errors are introduced into the series. When the best linear approximations to the displacement method of forecasting are applied to actual weather data, the formulas obtained are nearly the same as those previously established by standard linear regression methods. It is concluded that only slight future improvement in short-range prediction of pressure can be expected from linear formulas, but that nonlinear formulas may yield great improvement.

J. R. Lumby (A and M College of Texas, College Station, Texas) *Present Status of the Data Center (A) for Oceanography*—Oceanographic data have been flowing fairly steadily into the center at the A and M College of Texas. Cruise data have been received from Brazil, Canada, France, Japan, The Netherlands, South Africa, the United States, and the U.S.S.R. Sea-level data have been received from Mexico, the United States, and the U.S.S.R. The records vary considerably in both form and content, especially as regards information subsidiary to the main data.

Iver A. Lund, Eugene J. Aubert, and Albert Thomasell, Jr. (Atmospheric Analysis Laboratory, Geophysics Research Directorate, Air Force Cambridge Research Center, Boston, Mass.) *Some Six-Hour Predictions Prepared by Statistical Methods*—Predictions of pressure, temperature, precipitation, cloudiness, and visibility were prepared using linear regression methods. Factor analysis techniques were employed for the purpose of isolating from a complex of variables a small number of factors which accounted for most of the predictand variation. A screening technique was used to select from the same complex of variables those few variables which when combined linearly provided the 'best' forecast.

Gordon J. F. MacDonald (Massachusetts Institute of Technology, Cambridge, Mass.) and Leon Knopoff (University of California, Los Angeles, Calif.) *The Chemical Composition of the Outer Core*—The average composition of the Earth is assumed to be that of chondritic meteorites. This assumption is consistent with the present rate of heat production in the Earth. An iron-nickel core is consistent with the chondritic model only if the upper mantle is mainly pyroxene, a condition inconsistent with seismic data. If the mantle is assumed to be made up of a 400-km shell of the composition of eclogite underlain by a material of the composition of dunite, the chondritic model requires a core of composition (Fe, Ni)$_{1.6}$Si. From the asymptotic relations in the Thomas-Fermi-Dirac model, the representative atomic number (r.a.n.) of Fe$_{1.6}$Si is 22.8. Bullen's density distribution gives a r.a.n. for the outer core of 22 ± 1. The composition of the core deduced from equation of state arguments is thus consistent with the chondritic model of the Earth. It is suggested that iron-silicide is formed by squeezing oxygen out of Fe$_2$SiO$_4$ at high pressures. The electrical conductivity of Fe$_{1.6}$Si is consistent with the requirements of dynamo theories of the magnetic field.

L. Machta (Office of Meteorological Research, U.S. Weather Bureau, Washington, D.C.) *On the Use of Carbon 14 as a Tool in Meteorology*—Carbon 14 is produced by the action of neutrons on atmospheric nitrogen and may be created either through cosmic-ray action or as a byproduct of nuclear tests. Naturally formed carbon 14, with its 5600 year half-life, is uniformly distributed throughout the atmosphere as carbon dioxide. Differences in the ratio of carbon 14 to stable carbon in CO$_2$ may reflect an increase in stable carbon due to the growth of CO$_2$ from the burning of fossil fuels. It has been suggested that the bulk of the weapon carbon 14 was carried by the rising atomic cloud into the stratosphere. Measurements of its reappearance at the ground yield clues as to the removal locations and times from the stratosphere. Quantitative computations are hampered by a lack of knowledge of the initial stratospheric source strength, CO$_2$ exchange rate with oceans, and utilization by plants.

Royal R. Marshall (Enrico Fermi Institute for Nuclear Studies, University of Chicago, Chicago, Ill.) and David C. Hess (Argonne National Laboratory, Chicago, Ill.) *Lead from Stone Meteorites*—Microgram quantities of lead have been separated from several chondrites by volatilization from graphite crucibles at 1200–1400°C. Mass spectrometric analyses have been made on approximately one microgram amounts using boric acid with tantalum filaments. As compared to the PbS method, this technique of placing the lead on the filament raises the strength of the ion beam for small samples by about an order of magitude. The leads from Holbrook, Beardsley, and Plainview are substantially less radiogenic than modern average crustal lead. The concentrations in these meteorites are a few tenths of a ppm, several times as high as found for Richardton and Forest City, which have no more than about 0.1 ppm. Richardton has considerably more radiogenic component than typical terrestrial lead, but somewhat less than found by Patterson for the Nuevo Laredo meteorite. The same lead-lead age, 4.6×10^9 yr, is deduced from both leads. Ages from the others range to somewhat lower values. The concentrations of lead are 1.5 to 3 times as great as should result from the observed amounts of uranium and thorium. Also, the ratios of thorium to uranium appear to be closer to 3 than to 4. Terrestrial values of this ratio are typically between 3.5 and 4.5.

M. Martinelli, Jr. (U.S. Forest Service, Rocky Mountain Forest and Range Experiment Station, Ft. Collins, Colo.) *Some Hydrologic Features of Alpine Snowfields under Summer Conditions*—Ablation, density and weather factors were measured at selected snowfields in the Front Range of Colorado during the summers of 1955 and 1956. Water equivalent of ablation and moisture exchange between the atmosphere and the snow surface were computed. Weekly ablation varied from 2.8 ft on a southern exposure in late August to 1.1 ft on a northern exposure in mid-September. Ablation averaged 1.92 ft per week for July, August, and the first half of September. Snow density increased during the summers, reaching well over 0.70 during August and then decreasing slowly. For each acre of snow existing on August 1, about 11-½ ac ft of water were released by ablation during July and August. This amounted to 0.19 ac ft of water per day per acre of snow. Sverdrup's equation indicated the net moisture exchange between the atmosphere and the snow averaged less than two per cent of ablation. Proposals are made to sustain stream-flow into the summer by the construction of barriers to drift additional snow and by the application of materials to the snow surface to regulate melt.

John T. McCabe and Thomas D. Potter (Headquarters, Air Weather Service, Directorate of Climatology, Andrews Air Force Base, Washington, D.C.) *A Method for the Construction of Climatological Fallout Patterns*—Given the target location, the climatological period (month or season), the fission yield of the weapon, and a critical radiological dose (or dose-rate), a method of finding the frequency that areas about the target will be affected by radioactive fallout of the critical dose is presented. If the actual effective winds, which distribute the fallout particles, are not available, the assumption of a circular normal distribution of the effective wind is made. This distribution can be obtained by C. E. P. Brooks' method or, if the points are numerous, by a mechanical method described herein.

John F. McClay and Paul F. Fougere (Air Force Cambridge Research Center, Bedford, Mass.) *Mutually Consistent Spherical Harmonic Analysis*—New method derives a single set of coefficients A_n^m, B_n^m, α_n^m, β_n^m in spherical harmonic expansion using component data obtained on an arbitrary discrete grid covering a spherical surface. Applies equally well to main field and to secular variation. Since the basis functions P_n^m, X_n^m, and Y_n^m of Schmidt do not form orthogonal sets over an arbitrary grid, simple linear combination of such basis functions which are orthogonal, are obtained in a simple manner. Having expanded the experimental data in a sufficiently large set of such orthogonal functions, it is then easy to determine, by means of the variance ratio test, which members of this set are really useful in representing the original data. Results are obtained in such a way that not only are best fits to the data obtained but also the derived functions are necessarily mutually consistent.

William T. McGuinness and William L. Donn (Lamont Geological Observatory, Columbia University, Palisades, N. Y.) *The IGY Island Observatories: Atlantic*—Part of the IGY oceanographic program involves instrumentation and data collection at a number of fixed island sites (Island Observatories). A description will be given of the Atlantic (and one Indian Ocean) installations together with a report on the progress of data gathering to date. New instrumentation will be described.

R. P. Meyer, J. S. Steinhart, and G. P. Woollard (Department of Geology, University of Wisconsin, Madison 6, Wisc.) *Seismic Determination of Crustal Structure in the Central Plateau of Mexico*—A series of explosions at Durango, Mexico, were recorded along a line southeast from Durango on the Central Plateau of Mexico. The area is characterized by Bouguer anomalies of about −200 mgal. A study of the geologic structure was made and the crustal section down to the Mohorovicic discontinuity determined. Preliminary results indicate a depth to Moho of about 40 km.

Donald S. Miller and J. Laurence Kulp (Lamont Geological Observatory, Columbia University, Palisades, N. Y.) *New Isotopic Data and the Colorado Uranium Mineralizations.* Isotopic measurements on lead from primary pitchblende and intimately associated galena, as well as isotope dilution analyses of uranium and lead in the pitchblende, restrict the area of speculation concerning the origin of the uranium mineralizations of the Colorado Plateau. (1) Concordant ages at both 50 and 200 m y preclude the hypothesis that all deposition took place at the end of the Mesozoic with the higher apparent ages due to contamination by old (that is ~1.0 b y) radiogenic lead from the basement. (2) Identical lead isotopic composition of the pitchblende and galena from the Divide Mine, show that very recently (that is, since 5 m y ago) either deposition occurred here, and possibly throughout the Plateau, or recrystallization with loss of lead occurred. (3) The high radiogenic lead in the Plateau galenas appears to have been derived from a post-Cambrian source.

	Pct 208	Pct 207	Pct 206
K-174 Pitchblende	92.6	5.70	1.68
P-271 Galena	92.7	5.65	1.63

An hypothesis which appears to account for all of the data requires leaching of uranium and lead from a 120–180 m y old tuffaceous source in the sediments with some random leakage prior to the leaching. Proper conditions of ground water circulation may have occurred at one or more periods from about 100 m y ago to the present. In most cases the uranium and radiogenic lead were redeposited close to their source and incorporated in both galena and pitchblende.

R. A. Minzner (Geophysics Research Directorate, Air Force Cambridge Research Center, Bedford, Mass.) *Atmospheric Density from Recent Rocket and Satellite Measurements*—The ARDC Model Atmosphere was based on esentially all upper atmosphere data available at the time of its preparation. Theoretical considerations determined the higher altitude portions of the model. Recent density data up to 200 km altitude, from rocket-borne gages as well as data deduced from orbits of artificial Earth satellites, greatly extend the altitude range of direct observations. Marked diurnal and seasonal variations in some rocket data suggest that atmospheric density at high altitudes is strongly influenced by solar radiation on the atmosphere below the point of measurement. Satellite data from three independent sources are compared with rocket data and with the ARDC Model. Values of densities inferred from orbits of 1957 $\alpha 1$, 1957 $\alpha 2$, and 1957 β are generally self-consistent, but are markedly higher than rocket data. Five satellite-inferred data points between 200 and 275 km suggest an atmospheric density model with densities about eight times those of the ARDC Model. The apparently higher densities from satellite observations may be due in part to additional drag forces of electrostatic origin. Atmospheric models based on satellite drag data will be useful in predicting satellite lifetime but may not necessarily represent true atmospheric density.

J. Murray Mitchell, Jr. (Office of Climatology, U.S. Weather Bureau, Washington, D.C.) *A New Test for Homogeneity of Historical Temperature Records*—A new method of testing the homogeneity of historical temperature series is described which is tailored to the typical characteristics of climatological stations in the United States (station density, length and continuity of records, station history knowledge, etc.). It minimizes several objections to existing homogeneity tests, and is usually capable of describing with statistical significance a slippage of mean of about 0.5°F or more in the period of record at a station due to an inhomogeneity. The feasibility of a similar test for precipitation data will be considered.

J. Murray Mitchell, Jr. (Office of Climatology, U.S. Weather Bureau, Washington, D.C.) *Effect of Changing Observation Time on Mean Temperature*—A study of hourly temperature data at several stations in the United States is described which reveals the effect of arbitrary changes in observation time on the homogeneity of monthly mean temperatures at climatological stations. Results show that the greatest possible effect varies with place and season between less than ½°F and more than 3°F. An example is given to show to what extent the failure of cooperative observers to document observation time changes typically vitiates evidence of secular trends. Evening observations are concluded to be more homogeneous than morning observations.

Walter H. Munk and Richard Haubrich (University of California, La Jolla, Calif.) *The Polar Tide*—We have obtained the energy spectrum of sea level from mean monthly values at each eleven localities. The average record length at the eleven localities is a century. A peak at one cycle per 14 months is identified as the polar tide caused by the Chandler wobble.

Jerome Namias (Office of Meteorological Research, U.S. Weather Bureau, Washington, D.C.) *Improvements in Extended Forecasting Resulting from Employment on Numerical Methods*—Several months experience with numerical predictions of midtropospheric flow patterns carried on with the help of electronic machines is summarized. Although the machine products must still be modified in obtaining five-day prognoses, they have made the forecast procedure easier, speedier, more physical, and objective. More important the results are encouragingly better than the averages of recent years.

Cecil A. Nanney (U.S. Naval Research Laboratory, Washington 25, D.C.) *A Study of Correlations between Earthquakes and Microseisms*—In August, 1954, an investigation was begun to determine whether any correlation existed between earthquakes and microseisms. The study was based largely on previously published microseism data from a number of widely separated stations. It included over three years of microseism data and about 400 documented earthquakes. Because of the relatively frequent occurrence of earthquakes and the apparent effect of various phenomena on microseisms, the study has utilized statistical procedures of sampling and measuring correlations. The study has disclosed that: (1) The microseism frequency (inverse period) and amplitude were found to increase before the occurrence of many large earthquakes ($M \gtrsim 6\text{-}\frac{1}{2}$) and to decrease after their occurrence; (2) deep earthquakes, though not necessarily large, were found to be associated with a similar behavior of the amplitude of microseisms; (3) the study showed that smaller earthquakes were often associated with local increases of microseism amplitude and frequency; (4) very long-period (>10 sec) microseisms were found to be correlated with deep earthquakes; and (5) there was some indication that the propagation direction of microseisms may be associated with the location of significant earthquakes. The findings (1) to (4) are based on a statistical significance level of 0.1.

Chester W. Newton and Harriet R. Newton (Department of Meteorology, University of Chicago, Chicago, Illinois) *Interactions between Large Convective Rainstorms and Environmental Wind Field*—Because of vigorous vertical interchange of horizontal momentum, large convective cloud systems can maintain horizontal velocities appreciably different from that of the ambient air, if the environment is characterized by strong vertical shear. Under jet-stream conditions typical for squall lines, estimated relative motions are of the order 10 m/sec. By analogy with hydrodynamics experiments, it is estimated that non-hydrostatic pressures of 0.5 to 1.0 mb or more may result from such relative motions, near the boundary of the convective system. Variations of the non-hydrostatic pressure with height (because of varying relative motions at different levels) may cause vertical accelerations of the same magnitude as ordinary thermodynamic buoyancy forces. This effect can account for directionally-organized propagation of existing convective systems, which appears to be in good agreement with the observed behavior of large rainstorms as analyzed by use of hourly rainfall amounts.

Walter Nichiporuk and Arthur Chodos (Division of Geological Sciences, California Institute of Technology, Pasadena, Calif.) *Concentration of Vanadium, Chromium, Cobalt, Nickel, and Zinc in the Troilite Phase of Meteorites*—Chemical and x-ray fluorescense methods have been applied to a study of vanadium, chromium, cobalt, nickel, and zinc in troilites from iron and silicate-iron meteorites. The results show that the two kinds of troilite are chemically indistinguishable. Their concentrations of vanadium are low and vary over a narrow range whereas those of cobalt, nickel, and copper vary over a broad range. Different occurrences of troilite within the same meteorite also show considerable variations. The concentrations of zinc appear to be grouped within two distinct regions, one in the proximity of 55 ppm and another above 200 ppm.

Matthew F. Norton and Ross F. Giese, Jr. (Department of Geology, Columbia University, New York 27, N. Y.) *The Role of Wrench Faulting in Orogeny*—The hypothesis that seismic activity in island arcs and fold belts results from basement faulting with a dominant wrench component suggests the corollary that rotation of basement blocks creates some limited basins of sedimentation and elsewhere differentially elevates overlying sediments which then deform under gravitational stresses. The present geology of the Cayman-Puerto Rico trench system appears to illustrate this. Belts of cataclasites, secondary shears, and deformation within taphrogeosynclines in the piedmont of eastern North America define a similar ancient zone which parallels Appalachian folds and is similar in magnitude to the San Andreas system. While rotation along basement wrench faults may initiate sedimentary deformation, its style depends on sediment thickness. Thin shelf sediments are fault-folded and often intensely metamorphosed; geosynclinal sediments undergo alpino-type deformation; and stresses in the already-segmented cratonal basement are relieved by relative movement of blocks with en echelon faulting of overlying sediments.

✓ John A. O'Keefe (U.S. Army Map Service, Washington 25, D.C.) *Report of AGU Committee on Geodetic Applications of Artificial Satellites*—Two meetings of this group have been held. At the first meeting, held in December 1957 on an informal basis, it was recommended that data on regression of the nodes of existing satellites be furnished geodesists as soon as possible. Another recommendation emphasized the need for fresh tracking data, that is, data obtained at comparatively short distance intervals during an orbital revolution.

A second meeting of the Committee was held at Boston, Mass., early in March 1958. The Committee received with great appreciation a report by Luigi G. Jacchia, Smithsonian Institution Astrophysical Observatory, on the basic orbital data for Satellite 1957 Beta during the period November 4, 1957, to February 10, 1958. Major conclusions of this meeting were: (a) In view of the critical need for new studies of satellite orbital theory, experts in celestial mechanics should be relieved from other duties as far as possible and allowed to pursue these studies, and (b) for geodetic purposes, satellite perigees should be as high as possible, consistent with accurate observability. A perigee figure of 1000 km was suggested as a minimum.

Jack Oliver and Maurice Ewing (Lamont Geological Observatory, Columbia University, Palisades, N.Y.) *Short-period Oceanic Surface Waves of the Rayleigh and First Shear Modes*—Waves corresponding to the short-period segment of the Rayleigh mode and to the first shear mode are identified for paths traversing the deep ocean, apparently for the first time. It appears that the reason for the presence of the waves in this case and their conspicuous absence in all other cases is that (a) the shock which excited these waves is the atomic explosion of Operation Wigwam, deep in the Pacific Ocean, (b) earthquake sources are generally too deep to excite short-period waves efficiently. The new data strongly support the normal mode explanation for the dispersion of Rayleigh waves crossing the Pacific Ocean and furnish supporting evidence for the crustal structures previously deduced from surface wave dispersion and from refraction shooting. The unusual characteristics of the body phases and the T phase may probably be explained as well by assuming the source was within the water layer.

Philip M. Orville (Geophysical Laboratory, Carnegie Institution of Washington, Washington, D.C.) *Composition of Unzoned Pegmatites in Southern Black Hills, South Dakota*—Three unzoned pegmatites of contrasting texture and structure in the vicinity of Keystone, South Dakota, have been studied in detail in the field and laboratory. They occur within Precambrian quartz-mica schist country rock and are peripheral to the Precambrian Harney Peak granite. The bulk composition of each pegmatite has been determined and comparison of their chemical compositions shows them to be almost identical. Compositions of the Harney Peak granite have also been determined at two localities and these are very close to the pegmatite compositions. The modal compositions of the pegmatites and the Harney Peak granite are approximately 15 pct microcline, 40 pct albite, 35 pct quartz, and 10 pct muscovite. The nearly identical pegmatite compositions and their close correspondence to the composition of the Harney Peak granite suggest a common source of granitic magma of uniform composition for both the pegmatites and the Harney Peak granite.

Hans A. Panofsky and V. R. K. Rao (Pennsylvania State University, University Park, Pa.) *The Relation between Lagrangian and Eulerian Correlation*—The observations of dispersion of SO_2 in project Prairie Grass are used to determine Lagrangian correlation coefficients. These are compared with simultaneous Eulerian coefficients. Although the Lagrangian coefficients are not well determined by the observations, particularly at daytime, the results are consistent with the hypothesis that Lagrangian and Eulerian correlation functions have the same shape but different time scales. In particular, both show similar diurnal variations. At night, when the coefficients are best determined, the ratio of Lagrangian time scale to Eulerian time scale is of order 3.

H. V. Peterson (U.S. Geological Survey, Denver Federal Center, Denver, Colo.) *Erosion and Sediment Problems on Western Arid Lands*—Erosion on arid lands differs from erosion in humid areas mainly in extent and intensity. Sheet erosion, rilling, and gullying in more humid localities occur in the West, but gullying is by far most serious. In many areas erosion evolves from gully cutting to extensive sheet erosion and rilling, and finally to badland formation. Widespread gullying has resulted from: (1) the prevalence of alluvium-filled valleys susceptible to cutting; (2) aridity, with its characteristic relatively wide range in magnitude and intensity of rainfall and runoff resulting in a precarious balance between protective vegetation and erosion; and (3) distinct changes in land use following settlement. Sediment from gullying, and subsequent development of sheet erosion and rilling deteriorating into badlands, can be measured accurately. Potential sediment from untreated areas can be predicted. Hydraulic action of streamflow transports the sediment through the drainage system, and eventually out of the basin. Attempts at treatment have varied. Earliest efforts were designed to "keep the raindrop where it falls." Later the principle of flood control was stressed. Most recent efforts aim to restore the valley floors through induced aggradation and refilling of the gullied channels.

B. B. Phillips and Gilbert D. Kinzer (Office of Physical Research, U. S. Weather Bureau, Washington, D. C.) *Measurements of the Size and Electrification of Droplets in Cumuliform Clouds*—The size and the free electric charge of more than 6000 individual natural cloud droplets have been measured. The measurements were made at a mountain laboratory in southeastern United States in stratocumulus clouds and in thunderstorm-associated clouds. Stratocumulus clouds with fair-weather electric fields were found to have approximate Gaussian charge distributions symmetric about zero charge. The magnitude and distribution of charge observed on these non-storm clouds approach values described recently by R. Gunn in his theory of aerosol electrification by the diffusion of environmental light ions. Thundercloud droplets were highly electrified and within given cloud volumes the droplets were charged entirely positive, entirely negative, or fractionally positive and negative.

Willard J. Pierson, Jr. (College of Engineering, New York University, New York, N. Y.) *Linear and Non-Linear Problems in Wave Theory for Waves Influenced by Both Gravity and Surface Tension*—Recent results by G. D. Crapper show that the troughs of pure capillary waves point into the water sharply and that the crests are rounded. This is the opposite to the behavior of gravity waves. It is shown that for a wide range of wave frequencies neither the usual gravity wave approximation nor the usual capillary wave approximation is very good. It is also shown that the change-over in appearance takes place at a wave length of 2.44 cm, and that the waves may even be steeper than the /λ value of 0.730 given by Crapper for capillary waves.

Donald J. Portman (Willow Run Labs., University of Michigan, Ypsilanti, Mich.) *Conductivity and Length Relationships in Heat-Flow Transducer Performance*—In recent years many investigators have used thermoelectric heat flow transducers to measure heat conduction in natural soil. If the transducer has thermal properties different from those of the soil, it will interfere with the natural heat transfer and an error in measurement will occur. An analysis of the error for a transducer placed in an infinite medium in steady-state conditions is made in terms of two non-dimensional parameters: (1) the ratio of transducer conductivity to soil conductivity and (2) the ratio of transducer thickness to transducer width. An exponential relationship is postulated on the basis of physical considerations and is verified by the results of an electrical analogy experiment for a square transducer having a thickness-width ratio of 0.125 for conductivity ratios from about 0.1 to 2.2. An error of -60 pct was found for a conductivity ratio of 0.1 and an error of $+5$ pct for a conductivity ratio of 2.2. The results are used to estimate error in measurements made during the Great Plains Turbulence Field Program.

Frank Press (Seismological Laboratory, California Institute of Technology, Pasadena, Calif.) *Velocity Distribution in the Crust*—Seismic determinations of crustal structure are sensitive to the vertical velocity distribution within the crust. This distribution is inherently difficult to observe. The available data are reviewed and new evidence is presented from the Corona blast of February 18, 1958. It is concluded that the upper part of the crust is characterized by compressional and shear velocities of 6 and 3.5–3.6 km/sec. Evidence is presented for a layer with compressional velocity of 7.2–7.4 km/sec occurring at a depth of about 20 km under California and Nevada. The implications of this layer on determination of crustal thickness by explosion seismology and surface wave phase velocity methods are discussed.

Donald R. Purdy (U.S. Naval Research Laboratory, Washington, D.C.) *Some Examples of the Variability of Winds at 300 mb*—Data from a limited number of transosonde flights have been processed to yield small-scale (two to five minutes) fluctuations in the winds. Spectrum analyses of these preliminary wind data are presented as well as the rates of turbulent dissipation of energy per unit mass ϵ. The latter were calculated using a formula developed by Batchelor relating ϵ to the mean-square acceleration of the winds.

R. O. Reid (Department of Oceanography and Meteorology, A and M College of Texas, College Station, Texas) *Effect of Coriolis Force on Edge Waves: I, Investigation of the Normal Modes*—Free edge waves on a sloping continental shelf in the presence of Coriolis force differ from purely gravitational edge waves in several important respects. In general, there exist two classes of waves for a given mode. The waves of the first class can move in either direction along shore; however, for a given longshore wave length, the speed for waves moving to the right (when facing the shore from the sea side) exceeds the speed of the waves which move to the left. The waves of the second class are essentially inertial boundary waves with very slow speed and, like Kelvin waves, move only to the left. Another important feature of edge waves on a rotating Earth is that the group velocity has a finite upper limit for waves of very great length. In the case of the fundamental mode of the first class (modified Stokes edge wave on a rotating Earth), the limiting group velocity is gs/f, where g is the acceleration due to gravity, s the shelf slope, and f the Coriolis parameter. For the fundamental mode, only the first-class waves can exist and the difference in magnitude of the phase velocities for propagation to the right or left is equal to f/k for any longshore wave number k.

Irvin C. Reigner (U.S. Forest Service, Northeastern Forest Experiment Station, Kingston, Pa.) *Prediction of Streamflow for Single-Watershed Calibration*—Six year's daily streamflow, precipitation, and temperature data were used to develop equations for the prediction of monthly and annual runoff, and peak flow from a 1500-acre scrub oak watershed in northeastern Pennsylvania. Standard errors of estimate were used to determine the length of streamflow records necessary to detect small differences in flow caused by converting the scrub oak cover to a high forest of mixed conifers and better hardwoods. Monthly streamflow was predicted using a weighted and exponential expression of monthly precipitation and an estimate of storage at the beginning of the month. The latter parameter was derived from an antecedent precipitation value and antecedent temperature. Annual streamflow prediction is based on the water balance equation: runoff = precipitation − water loss ± storage change. An equation has been derived using these independent variables: annual precipitation, mean annual temperature, and estimated storage change. The latter is the difference between beginning and ending storage, both derived as above. Peak flows were estimated from a multiple regression involving storm precipitation weighted on an hourly basis and a total storage factor derived as above.

Roger Revelle (Scripps Institution of Oceanography, University of California, La Jolla, Calif.) *The Downwind Expedition to the Southeast Pacific*—As part of the oceanographic program of the International Geophysical Year, the research vessels *Horizon* and *Spencer F. Baird* carried out, during the period October 21, 1957, to February 28, 1958, a voyage of exploration to the Southeast Pacific. The total distance logged by the two ships was about 40,000 miles. The program of investigation included measurements of atmospheric and oceanic carbon dioxide; studies of the chemical and physical properties of the water, including its carbon 14 content; bottom sounding, dredging, coring, and photography; and seismic refraction and reflection studies of crustal structure and thickness. Some 35 measurements of the heat flow through the sea floor indicate the existence of a definite pattern with high values near the East Pacific Rise and low values near the South American trenches and in some areas west of the Rise. The highest values were about 40 times the smallest. Seismic velocities greater than 7.5 km a second were not obtained in the region of highest heat flow. The echo sounding results indicate that the major features of the sea floor topography of the Southeast Pacific form a reticulate pattern of basins and ridges and are considerably more complicated than has previously been supposed. Guyots were found and dredged in several areas. The rate of sedimentation in much of the region seems to be very slow: in many places manganese nodules cover about a fourth of the bottom.

Oscar E. Richard (Headquarters, Air Weather Service, Directorate of Climatology, Andrews Air Force Base, Washington, D.C.) *Comparison of Methods of Computing Degree Days*—Recent work on the computing of degree days brought to light a distinct variance in the number of degree days computed for maritime stations using a method recently developed by R. G. McGrew, AWS, 2nd Weather Wing, Technical Support Branch, as against the method in more common use developed by H. C. S. Thom, U.S. Weather Bureau, about 1942. The two methods give comparable results for stations under a continental climatic influence. The results of a comparison of these methods against observed data will be presented here.

Adrian F. Richards (U.S. Navy Hydrographic Office, Washington 25, D.C.) and James M. Snodgrass (Scripps Institution of Oceanography, La Jolla, Calif.) *Volcano Acoustics*—Frequency analyses were made from magnetic tape recordings of airborne sounds originating from three volcanic eruptions. Both the September 1950 and January 1954 eruptions of Ō-sima Volcano, Japan (recorded by the NHK Broadcasting Bureau, Japan) were strong harmonic progressions with an apparent fundamental frequency of the first at 11 cycles and of the second at approximately 16–17 cycles. The lower limit of the analyses was ten cycles. Little indication of a resonant frequency appeared from the analysis of an eruption of Izalco Volcano, El Salvador (recorded by H. Young and L. Pugsley) in 1956; essentially broad-band acoustic energy was present from 20 cycles, the lower limit of analysis, to about 3000 cycles. All analyses made to date show energy maxima between about 100 and 200 cycles; however, the absence of maxima below this limit may result from instrumental attenuation of the low frequencies. Recent attempts to investigate underwater volcanic acoustics in the Pacific and Atlantic Oceans will be briefly discussed.

H. C. Riggs (U.S. Geological Survey, Washington 25, D.C.) *Regional Frequency of Low Flows of Streams*—The low-flow frequency relation based on observed minimum annual discharge at a gaging station is a function of stream-basin characteristics and of chance variation. Removal of the chance variation should adjust the relation so that it will better represent future events. This is done by using an equation which relates discharge at 20-year recurrence interval to (1) discharge at two-year recurrence interval, (2) drainage area, and (3) slope of the base-flow recession curve and in which the residual error of the correlation is largely due to chance variation. Such equations are presented for eastern United States. They may be used for stream sites having a minimum of discharge information as well as for gaged sites.

J. C. Rose, G. P. Woollard, and R. M. Iverson (Department of Geology, University of Wisconsin, Madison 6, Wisc.) *Gravity Standardization Measurements with the Gulf Pendulums in Australia and New Zealand*—The Gulf quartz pendulums have been used by the group at the University of Wisconsin for observations in the Pacific area and in the Antarctic. In 1956–1957 new Gulf stations were established at Christchurch, Wellington, Hastings, and Dunedin in New Zealand; Melbourne, Sydney, Brisbane, Townsville, Cairns, and Darwin in Australia; and Ross Island in the Antarctic. The sites at San Francisco and Honolulu were reoccupied. In 1958, observations were made at earlier Gulf sites at San Francisco, Honolulu, Manila, Tokyo, Darwin, Cairns, Townsville, Brisbane, Sydney, and Christchurch, and new Gulf stations were established at Okinawa, Hong Kong, and Singapore. The results appear to have an accuracy of ±0.5 mgal based on the standard error of the closure stations. The previous photographic recording methods have been changed to a completely electronic system using a photomultiplier and slit system with an electronic interval timer. This has resulted in great simplification in calculations of the results.

E. H. Roseboom, Jr., and G. Kullerud (Geophysical Laboratory, Carnegie Institution of Washington, Washington, D.C.) *The Solidus in the system Cu-Fe-S between 400 degrees and 800 degrees C*—The solid phases in equilibrium with a sulfur-rich melt and a vapor were determined by heating mixtures of the elements or of copper and iron sulfides plus sulfur in sealed and evacuated silica tubes with sulfur in sufficient excess to form a liquid as well as a vapor phase. Phases were identified by reflecting microscope and x-ray diffractometer. The phases encountered were pyrite, pyrrhotite, covellite, digenite, 'chalcopyrite-cubanite,' and the 'Cu_5FeS_6' phase described by Merwin and Lombard. The following pairs of phases are stable with a sulfur-rich melt and a vapor over the following temperature ranges: pyrite + covellite, $< 434 \pm 3°$; covellite + 'Cu_5FeS_6,' $434 \pm 3°$ to $485 \pm 2°$; 'Cu_5FeS_6' + pyrite, $434 \pm 3°$ to $498 \pm 4°$; covellite + Fe-bearing digenite, $485 \pm 2°$ to $507 \pm 2°$; Fe-bearing digenite + 'Cu_5FeS_6,' $485 \pm 2°$ to $498 \pm 4°$; Fe-bearing digenite + pyrite, $498 \pm 4°$ to $568 \pm 3°$; Fe-bearing digenite + 'chalcopyrite,' $568 \pm 3°$ to $>800°$; 'chalcopyrite-cubanite' + pyrite, $568 \pm 3°$ to $739 \pm 3°$; Cu-bearing pyrrhotite + pyrite, $739 \pm 3°$ to $743 \pm 3°$; 'chalcopyrite-cubanite' + pyrrhotite, $739 \pm 3°$ to >800.

Five phases are stable at each of the above temperatures, which represent invariant points. As the melt and vapor phases contain very little Cu and Fe, the pressure at these invariant points is probably slightly lower than that of pure saturated sulfur vapor. In the presence of a sulfur-rich liquid and a vapor at 739°C, the solubility of copper in pyrite is less than a half per cent by weight but exceeds three per cent in pyrrhotite. At 700°C, 'chalcopyrite-cubanite' forms a continuous phase from Cu_6Fe_4 to Cu_3Fe_7. Digenite forms a continuous phase to $Cu_{70}Fe_{30}$ at 700°C to $Cu_{82}Fe_{18}$ at 568°C, and to $Cu_{88}Fe_{12}$ at 500°C.

J. H. Rosenbaum (Shell Development Company, Houston, Texas) *A Note on the Propagation of a Sound Pulse in a Two-layer Liquid Medium*—The contribution from the branch line integral in Pekeris formulation of the propagation of explosive sound in a two layer liquid medium (Geol. Soc. Amer. Mem. 27, 1948) is investigated. It is shown that there is no net contribution to the solution, in terms of pressure amplitude measured in the upper layer, which decays less rapidly than r^{-2}, where r designates the horizontal range, which is large compared to the depth of the layer. This result is applicable to early arrival pressure signals and is in agreement with recently published model experiments by W. C. Knudsen in the Journal of the Acoustical Society of America.

R. D. Russell, R. M. Farquhar (University of Toronto, Toronto, Ont., Canada), and R. L. Stanton (The University, Armadale, New South Wales, Australia) *A Revised Interpretation of the Isotope Ratios of Common Lead*—It is well known that the model proposed by Alpher and Herman for the interpretation of common lead isotope abundances explains the essential features of these abundances. It is also known that small systematic deviations occur, which have been explained on various occasions by the extraction of lead systematically with time from rocks of different lead abundances, and by the systematic alteration of the proportions of these elements in a single source rock from which all leads may come. A basic difficulty in pursuing the nature of the deviations has been the uncertainties in identifying anomalous leads and excluding them from the analysis. In several papers published since 1955 by one of us (R. L. S.) a mechanism has been put forward for the genesis of a certain class of lead ores of the conformable type. It is an essential feature of this theory that the lead is derived directly from the Earth's mantle and formed into galenas; contact is made only with surface rocks of known types for a very limited period of time. Therefore, it follows that the probability of these leads having received anomalous additions of radiogenic lead from surface rocks is very small. We thus consider these leads to be primary and all vein leads to have travelled finite distances through surface rocks and therefore to be potentially anomalous.

Of the available lead isotope analyses we are able to find only a few that are of this conformable type. However, these leads all fit a single growth curve (that is, a single uranium-thorium-lead system) within a few tenths of one per cent. All the systematic deviations from a simple model referred to in the first paragraph vanish. One result of this hypothesis is that these galenas should be datable with excellent precision. There is a possibility that the class of leads we refer to here is the same as those described by Houtermans as 'B-type anomalous'.

O. A. Schaeffer and J. Zähringer (Chemistry Department, Brookhaven National Laboratory, Upton, L. I., N. Y.) *The Rare-Gas Contents of Iron Meteorites*—The rare gases in iron meteorites are present mainly as a result of nuclear reactions of cosmic-ray protons on the iron and nickel nuclei of the meteorites. At present, researches are being conducted to obtain information about the history and origin of meteorites by measuring the rare-gas contents of meteorites and measuring the production cross sections for the nuclear reactions of high-energy protons on iron which produce rare gases. The present level of mass spectrometric techniques is sufficient to study the reactions using high-energy protons from accelerators. We have been able to measure the cross sections of He^3 and He^4 production from iron for protons of 0.16, 0.43, and 3.0 Bev, as well as the cross sections for the argon and neon isotopes with 0.43 Bev protons. These results are used to interpret the rare-gas contents of several iron meteorites. Some results of this study are: (1) Present He^3-T ages should be lowered by a factor of 3, (2) a study of the A^{39} and Cl^{36} content of meteorites should yield information as to how long meteorites have been in space, and (3) from a study of He^3/He^4 ratios and especially Ne/He ratios it should be possible to obtain a depth-energy dependence of the rare-gas content and in this way possibly say something about the original size of meteorites when in space.

A. E. Scheidegger (Imperial Oil Limited, Calgary, Alberta, Canada) *Tectonophysical Significance of Fault-Plane Solutions of Earthquakes in the Northwest Pacific*—Fault-plane solutions of earthquakes are usually ambiguous to the extent that it is not known which of two orthogonal planes is the fault plane and which is the plane orthogonal to the motion vector (auxiliary plane). This makes it difficult to correlate fault plane solutions of earthquakes with tectonic features. To get around this difficulty, it has been proposed in the literature to investigate the B-axis, that is, the intersection of fault and auxiliary plane which is always uniquely defined. The writer has recently suggested in another paper, a physical significance for the B-axis by showing that the latter always lies in a plane normal to the axis of the tectonic displacement couple. This enables one to determine, from a series of fault-plane solutions of earthquakes in any one area, the tectonic displacement by a least-squares solution. This has been done for the areas marginal to the Northwest Pacific Ocean. In this fashion, the motion of the margin of the Northwest Pacific Ocean can be determined.

A. E. Scheidegger (Imperial Oil Ltd., 300 Ninth Avenue, West, Calgary, Alta., Canada) *The Random-Walk Model of Flow Through Porous Media*—Statistical methods have proven to be very successful in connection with the investigation of mixing effects that occur in ground-water flow. In pursuit of the idea of applying statistical mechanics to the theory of flow through porous media, the present paper investigates the implications of a random-walk model as opposed to random residence-time models. Although the random-walk model is physically not as satisfactory as other statistical models, it has the advantage of enabling one to investigate easily the effect of autocorrelation between subsequent time steps. It is shown that, if autocorrelation exists, the mixing process in porous media is governed by a telegraph equation rather than by a diffusivity equation. Expressions for the constants occurring in the telegraph equation are deduced in terms of other dynamical variables.

I. I. Schell (Tufts University, Medford, Mass.) *A Reconciliation of an Increased Circulation Characteristic of an Ice Age with a Decrease in Temperature and Solar Radiation*—It is shown that while an increase in the equator-to-pole temperature gradient and in the circulation could result from a simple increase in the temperature produced by an increase in the total solar radiation, a greatly increased equator-to-pole temperature gradient, circulation, evaporation, and precipitation characteristic of an Ice Age could occur only with a small decrease in temperature at the equator and large decrease at the poles produced by quite small but continuous decreases in the total solar radiation. It is estimated that the temperature during an Ice Age was −70°C at the North Pole and −100°C at the South Pole and that the temperature during an interglacial was 0°C and −30°C, respectively. This would permit ice in the Antarctic to exist during the entire period of the Pleistocene epoch as was previously indicated by Gould. It is also concluded from the uniform concentration of CO_2 over the globe, except for points near industrial sites, that changes in this gas could not account for the Ice Ages and for the recent amelioration in climates but may have slightly contributed to it.

G. F. Schilling and T. E. Sterne (Smithsonian Astrophysical Laboratory, Cambridge, Mass.) *Temperatures and Densities Inferred from Observations of USSR Satellites*—Surface observations of artificial earth satellites permit the application of relatively easy methods to calculate upper atmosphere densities from changes in the orbital elements due to drag effects. However, a substantial number of simplifying assumptions are implicitly involved in any such method developed to date, thus reducing the reliability of the results obtained from nonspherical satellites. Because of antenna effects, this includes all satellites which have been launched so far. Nevertheless, comparison of our numerical results based on observations of satellites 1957 $\alpha 1$, $\alpha 2$, and β, with those derived by other investigators, depicts a reasonable consistency which implies the need for a revision of existing model or standard atmospheres. It appears to us that the atmospheric density as well as the temperature above some 150 km altitude are appreciably higher than was usually thought before the availability of satellite data. In spite of the as yet low degree of accuracy of all numerical results, they necessarily influence not only the calculations of expected satellite life-times, but also the design characteristics for future satellites.

Allen H. Schooley (U.S. Naval Research Laboratory, Washington 25, D.C.) *Profiles of Wind-created Water-Waves in the Capillary-gravity Transition Region*—Crapper (1957) has theoretically predicted that pure capillary waves have profiles that peak downward, which is the reverse of the gravity wave case. This paper confirms Crapper's theory and shows enlarged profiles of capillary waves in a small water-wind tunnel that were photographed with a high-speed motion-picture camera. Under the conditions of the measurements, the maximum vertical distance between trough and crest for the capillary waves that were observed was about 0.5 wave length. This is roughly 70 pct of Crapper's theoretical figure of 0.73, and is about 3½ times the maximum of 0.14 for gravity waves. Wave profile pictures in the transition region from capillary to gravity waves are also shown. Examples are given where capillary waves having the same velocity as the gravity waves tend to ride just in front of the crests of the gravity waves.

Harry E. Schwarz (Corps of Engineers, U.S. Army, Washington 25, D.C.) *Simulation of a Reservoir System*—In developing river-regulation schemes, it is necessary to test the contemplated improvements and their operations against actual flow data to show the effects of the improvements. This usually is done by routing actual flows through the reservoir system. This gives an accurate picture of the operation of the system, but the method is time-consuming and not so well adaptable to the study of long time periods which are needed for conservation studies. Simplifying assumptions together with high-speed computation methods permit the simulation of a reservoir system in a form useful to the planning engineer. This paper describes a system of four reservoirs, one existing and three proposed, on the North Branch of the Potomac River, and develops a mathematical model of this reservoir system suitable for programming for an electronic computer of medium size.

A. L. Sharp (Agricultural Research Service, U.S. Department of Agriculture, Lincoln, Nebr.), A. E. Gibbs (U.S. Bureau of Reclamation, Lincoln, Nebr.), and W. J. Owen (U.S. Soil Conservation Service, Lincoln, Nebr.) *Problems Involved in Determining the Effects of Land Use and Treatment on Water Yields*—The disposition of precipitation and derivation of water yields as residuals are discussed. The parameters involved in these processes are enumerated and their effects explained. Problems involved in obtaining applicable data and computing results, with some possible methods of analysis, are considered. Use of plot and small-watershed data involves bridging the gap from small areas to large watersheds. The primary problem in determining effects of land use and treatment on water yields, from larger watersheds, stems from lack of directly applicable data. Large errors are probably involved in computation of watershed precipitation and determination of other factors. These errors increase inversely with the time period involved. It is possible to obtain at least periodic data on land use in watersheds, but obtaining quantitative data on the quality of vegetative cover is difficult. The number of variables involved in the generation of runoff is so great that use of electronic computers appears indicated in solutions of problems by multiple regression analysis.

Anatol J. Shneiderov (Polycultural Institution of America, 1241 New Hampshire Ave., Washington 6, D.C.) *On The Internal Temperature of the Earth*—A continuous influx of cosmic energy into the Earth has been determined as

$$E = k(2GM/rc^2)^2 \times (\beta Ms)^2 = 9 \times 10^{16}\ \text{ergs/sec} \qquad (1)$$

$k(2GM/rc^2)^2$ is gradient of pressure the flux produces in the Earth, G is gravitation constant, M is the mass, r is the radius, and δ is the mean density of the Earth, c is the velocity of light, β is the absorption constant of the flux (4×10^{-11} cm^2/gm), $s \oplus = 1 - (3/4)(r\delta\beta) + (2/5)(r\delta\beta)^2 - (1/6)(r\delta\beta)^3 + (2/35)(r\delta\beta)^4 - (1/60)(r\delta\beta)^5 \ldots$, and k being the unit of gradient in CGS system. Using the relationship $E' = \sigma T^{4\circ}K$, where $E' = E/4\pi r^2$, and σ is Stefan-Bolzman constant, T_{eff} of the Earth comes out 4.2°K, insolation and radioactive heat excluded, provided the entire influx of cosmic energy is radiated back into space. Heat flow from below the crust has been calculated to produce T_{eff}

of around 1°K. Therefore, about 3×10^{16} ergs are either stored in the interior of the Earth each second, or produce some geophysical work, or both. Checked for accuracy by calculating T_{eff} of over 80 various stars, and the planets, (1) produced values in satisfactory agreement with T_{eff} determined by other methods. Based on E' a formula for T as a function of δ' as density at a distance R from the center of the Earth has been developed

$$T = \{E'(b/\sigma)\,[0.5r^2(1 - R^2/r^2)]^{2/3}\}^{1/4} \quad \text{absolute degrees} \qquad (2)$$

b being a coefficient of proportionality. Expressed logarithmically for the Earth, (2) becomes

$$\log T\oplus = 0.424 + 0.5\log\delta' + 0.5\log s + (1/6)\log\{0.5r^2\,[1 - (R^2/r^2)]\}\,°\text{K} \qquad (3)$$

Assuming Bullen's distribution of density, (3) gives for T_{cent} 8900°K; surface of the core, 5770°K; and surface of the Earth 167°K if expenditure of energy for seismic and tectonic activities is not deducted. A curve of $T\oplus$ as a function of R and δ' has been drawn.

J. A. Simpson (Enrico Fermi Institute, University of Chicago, Chicago, Ill.) *Solar-Geophysical Aspects of Cosmic-Radiation Phenomena*—The intensity and energy spectrum of the cosmic radiation in the vicinity of the Earth changes dramatically within times ranging from the order of hours to the period of a solar cycle. The search for a theory of the solar origin for these cosmic ray changes with time is extending our knowledge of the solar influence upon electromagnetic conditions, both in interplanetary space and at the Earth.

John A. Simpson (Enrico Fermi Institute, University of Chicago, Chicago, Ill.) *What We Have Learned about Planetary Magnetic Fields and the Production of Cosmic Rays from the Flare of February 23, 1956*—This special flare event was unique for the magnitude of its cosmic-ray production and ionospheric effects at the Earth. From a detailed study of the solar flare, cosmic-ray propagation and storage in the solar system it is now clear that interplanetary magnetic fields exist. The available evidence favors an interplanetary field extending beyond the orbit of the earth. In addition, more intense fields exist in the vicinity of the sun which delay the escape of cosmic ray particles such that the delay depends upon particle energy.

R. H. Simpson (National Hurricane Research Project, U.S. Weather Bureau, West Palm Beach, Fla.) *Horizontal Eddies in the Hurricane Circulation*—Evidence of striated distributions of wind speed and of temperature in the hurricane circulation have been repeatedly found by research aircraft during the last several years. In 1957, simultaneous flights by two or more aircraft were made into hurricane Carrie on two occasions, once before and once after recurvature. Data collected on these occasions permit a more complete and quantitative examination of these striations and their role in hurricane circulations. The evidence is that this meso-scale feature is not a local result of convection in a rainband segment, but rather is a manifestation of a systematic eddy structure that permeates the circulation.

S. F. Singer (Physics Department, University of Maryland, College Park, Md.) *Role of Ringcurrent in Magnetic Storms*—E. N. Parker has thrown doubt on the existence of this ringcurrent. He concludes: (1) Even if it exists, the effects of the ringcurrent cannot be felt on Earth and therefore cannot give rise to magnetic storms because of the high conductivity of the Earth's outer atmosphere. (2) The main phase of magnetic storms can be explained in terms of an ionospheric current system. In our analysis of the problem of the origin of magnetic storms we reach conclusions which are directly opposite to those of Parker's. The main difference seems to be that we have considered the effect of a magnetic field on the anisotropic conductivity. In recent work, we investigated a physical mechanism (trapped protons drifting in the Earth's field) which produces an equatorial ringcurrent at a distance of five to ten Earth-radii.

H. F. Smith (Illinois State Water Survey, Urbana, Ill.) *The Effect of Urbanization on Runoff*—The hydrologic characteristics of two nearby watersheds, one urban, the other agricultural, have been compared. The two watersheds have similar relief and are comparable in area. The comparison shows that urbanization has considerable effect on peak flow, low flow, flow duration, and time of concentration.

J. B. Smith, Lela M. Jeffrey, and Donald W. Hood (Department of Oceanography and Meteorology, A. and M. College of Texas, College Station, Texas) *Evidence for the Presence of Carbamino Carboxylic Acids in Sea Water*—It has recently been observed in this laboratory that *Nitzchia closterium*, as well as other marine phytoplankton, utilize the carbamino complex of alanine in preference to inorganic carbon forms as a source of carbon for phytosynthesis. Since synthesis of significant amounts of carbon dioxide complex of alanine does not occur in water solutions except at pH values greater than 9.5, some doubt existed as to the significance of the observations to open sea conditions. Data have now been obtained which indicate that open sea water contains at least 5×10^{-8} moles of complex carbon dioxide per liter. The experimental procedure used to obtain these results were based on microbiological assay of organic concentrates isolated from sea water. The paper will include a discussion of the possible significance of these compounds to both the physical, chemical and biological systems in the sea.

Robert L. Smith, Irving Friedman, and William D. Long (U.S. Geological Survey, Washington 25, D.C.) *Welded Tuffs, Experimental I*—The authors investigated the welding and deformation rate of rhyolitic ash from the Bandelier formation of New Mexico as a function of temperature, water pressure, and load. The equipment allowed each of these variables to be varied independently. This paper will report on the results in the temperature range 535° to 735°C, H_2O pressure 50 to 300 lb/in², load of 100 to 528 lb/in², and times of from ten hours to five days. The maximum compaction of the starting material, 50 pct results in an obsidian-like black glass. Lesser amounts of compaction (shorter times) yields a glass ranging from a white loosely fritted mass, (~20 pct compaction) to a dark gray densely welded glass (>20 pct, <50 pct compaction). The rate of compaction (deformation) is strongly dependent on water pressure at water pressures from 0 to 50 pounds, and less strongly at higher water pressures. The rate dependence on water pressure increases at lower temperature.

W. Smith, I. Kaplan, and B. Herman (Office of Meteorological Research, U.S. Weather Bureau, Washington, D.C.) *The Life Cycle of the Meso-Systems Associated with the May 7–8, 1956 Severe Storms in Texas*—A detailed meso-analysis of a severe storm situation is presented with special attention given to the inception, the maximum intensity, and the dissipation of the meso-systems. Several features which may influence these phases of the life cycle are noted and possible implications presented.

Dewey R. Soltow and Richard D. Tarble (U.S. Weather Bureau, Washington 25, D.C.) *The Use of a Radar Beacon in Reporting Precipitation*—Increased use of radar has given hydrologists and meteorologists an excellent tool for improving the areal measurement of precipitation. It is often difficult to obtain rainfall reports from remote areas and during nighttime hours. As an aid in solving this problem, radar beacon techniques have been applied. As a result, a relatively inexpensive method of indicating accumulated precipitation on the PPI scope of the radar has been developed. Comparison of cost, maintenance, and reporting ability is made between the radar beacon and conventional radio-reporting raingages. Application of this type beacon to the reporting of river gage height and tide height is suggested.

William C. Spreen and Irving Solomon (Headquarters, Air Weather Service, Directorate of Climatology, Andrews Air Force Base, Washington, D.C.) *An Indirect Method for Estimating the Frequencies of Ceilings below Various Altitudes and within Various Altitude Ranges*—The solutions of many problems in applied climatology depend upon the further interpretation of available data through considerations of theory and a logical manipulation of the data. This paper describes an example of such a procedure whereby standard data summaries are arranged in a logical manner for a solution of the problem and, with further analysis based on background knowledge and theoretical concepts, reasonable estimates of values of unobserved parameters are attained.

Harris B. Stewart, Jr. (U.S. Coast and Geodetic Survey, Washington, D.C.) *Net Upstream Flow of Bottom Water in New York Harbor*—Approximately 100 hours of half-hourly measurements of current velocity and direction were obtained at the surface, mid-depth, and bottom at each of 17 stations arranged in four profiles across New York Harbor. Values for the velocity and duration of the flood and ebb currents allowed the calculation of the net non-tidal flow through the section represented by each meter. Net upstream movement near the bottom was found at each profile, with values ranging up to 19,000 ft^3/sec. At each profile the nontidal upstream flow subtracted from the nontidal downstream flow should represent the river flow at that time, and variations between profiles measured at different times should be attributable to changes in river flow. Comparison of the computed values with observed values from gaging stations metering river flow shows a lag between gaging and the arrival of a change of flow in the harbor. The rate of advance is about nine miles per day.

J. D. Stolarik, I. R. Shapiro, and J. P. Heppner (U.S. Naval Research Laboratory, Washington 25, D.C.) *The F-ΔD-ΔI Ground Station Magnetometers for Project Vanguard*—Analysis of satellite magnetic field measurements in terms of ionsopheric and extraterrestrial currents is dependent on accurate surface measurements taken reasonably close to the geographical locations where the satellite is interrogated. To obtain vector field measurements at the tracking-telemetering stations a magnetometer to measure absolute total field F, changes in declination ΔD, and changes in inclination ΔI was developed using a Varian proton precessional magnetometer as the sensing element. The reasons for undertaking this development were low cost, ease of installation and operation, and no calibration or temperature corrections. The magnetometers have been installed at Ft. Stewart, Georgia; San Diego, California; Havana, Cuba; Antigua Island; Quito, Ecuador; Lima, Peru; Antofagasta, Chile; Santiago, Chile; and Woomera, Australia. Errors in measurement are less than one gamma in total field, and less than 0.5 minute in declination and inclination. Operation of the magnetometers will be described.

G. W. Swenson, Jr. (University of Illinois, Urbana, Ill.) *Ionosphere Research Using Earth Satellites*—A review of the possibilities for the investigation of the morphology of the ionosphere by means of radio signals from man-made earth satellites. Several opportunities have already been presented, notably the launching of the USSR satellites transmitting on 20 and 40 mc/sec. Despite general lack of preparation at the time of launching and the lack of accurate orbital information throughout the radio life of these satellites, several interesting phenomena have been observed. Further opportunities are presented by the U.S. Satellites transmitting on 108 mc/sec, though the higher-frequency waves are much less affected by the ionosphere. Results obtained at the University of Illinois and elsewhere are discussed, and suggestions are made for future experiments. The possibility exists of determining the total electron content of the ionosphere, ionospheric inhomogeneities, and variation of ionospheric structure during normal and anomalous variations of solar radiation.

Howard E. Tatel[a], Merle A. Tuve, and Colleagues (Carnegie Institution of Washington, Washington 15, D.C.) *Carnegie Seismic Expedition to the Andes, 1957*—Because strong reflections were observed in 1954 and 1955 in the Rockies and Alaska from depths of 28 to 34 km, with high velocity rocks below this boundary (presumably the M-discontinuity), we undertook as our participation in the IGY a reconnaissance of the Andes Mountains and Plateau to seek evidence for the M-discontinuity under those high structures. Several open-pit copper mines at high elevations in Peru and Chile regularly use explosions of

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[a] Deceased November 15, 1957.

30 to 70 tons, which served as wave sources. During August to November 1957, using seven mobile seismometer stations, approximately 210 recording sites in Peru, Bolivia, and Chile were occupied for 35 large shots at Toquepala, Peru, and eight large shots at Chuquicamata, Chile. Approximately 60 records were obtained with amplitudes above the ground unrest. The waves were very strongly attenuated in paths across (under) the high plateau, and no reflections or velocities at depth could be determined for these paths despite rather strenuous attempts. Explosions of 50 tons produced no vertical wave motion as large as ½ Angstrom unit at distances of 280 km across the plateau, for example. Parallel to the western edge of the plateau, however, and at moderate altitudes of 6000 to 10,000 ft, reflections and velocities were observed. In the general vicinity of Arequipa, Peru, the upper velocity was about 6.2 km/sec and reflections from what appears to be the M-discontinuity with mantle velocity under it, were observed from a depth of about 34 km under average elevations of roughly 10,000 ft. In Chile, under elevations of roughly 5000 ft toward Antofagasta and Taltal from Chuquicamata, the upper velocity is about 6.0 km/sec, there is a faint indication of a 6.8 km/sec structure below this, and strong reflections indicate an M-discontinuity at roughly 55 km depth, with the mantle directly below it. The structures under the Andes appear to be highly non-uniform.

MORRIS TEPPER (Office of Meteorological Research, U.S. Weather Bureau, Washington, D.C.) *The Formation of Atmospheric Gravity Waves on an Inversion Surface by the Transit of an Upper-Air Isotach Maximum*—The transit of a steady upper-air isotach maximum in a one-dimensional stratified atmosphere is shown to produce gravity waves on an underlying inversion surface. Other conditions being equal, waves of greater amplitude are favored by the more intense and slower moving isotach patterns. Synoptic implications are discussed.

SIDNEY TEWELES (Office of Meteorological Research, U.S. Weather Bureau, Washington, D.C.) *A Study of Anomalous Warming of the Stratosphere*—Cross-sections through stratospheric warm cells show relative positions of polar night jet stream, tropospheric jet stream, and the various stratospheric air masses. Apparent interrelationship between the various elements is shown by a model.

T. P. THAYER (U.S. Geological Survey, Washington 25, D.C.) *Some Problems Related to Dating Peridotites and Intrusive Serpentinites*—The development of serpentinite chilled borders on intrusive peridotites, as suggested by Bowen and Tuttle, and the mobility of serpentinous rocks under stress present many problems. Where contacts are sheared and contact metamorphism is obscure or absent, masses intruded magmatically and serpentinized in place may be indistinguishable from 'cold' serpentinite intrusions. Erosional debris in surrounding sediments, or relations of closely associated rocks such as gabbro, may be the only reliable means of dating emplacement of the original magma. Peridotites of one age may be indistinguishable from others, even in a small district. The term diapiric is suggested to distinguish serpentinous rocks probably intruded secondarily, or 'cold', from peridotite known to have been serpentinized in place. The problems are illustrated in eastern Oregon, where a peridotite-gabbro complex intrudes Upper Permian rocks, and serpentinite masses intrude Upper Triassic strata. The Upper Triassic strata lie across the complex in places, and contain gabbro and peridotite erosional debris. The complex, therefore, must have been intruded in Early or Middle Triassic time rather than Jurassic, as once supposed. The serpentinite masses in the Triassic strata are regarded as diapiric.

H. C. S. THOM (Office of Climatology, U.S. Weather Bureau, Washington, D.C.) *The Distribution of Annual Tropical Storm Frequency*—The frequency distribution of annual tropical storm and hurricane frequency is examined for the southern North Atlantic Ocean and for storms reaching the United States coast. On the basis of physical and statistical hypotheses, it is found that the negative binomial distribution provides very good estimates of probabilities. The time trend in tropical storm frequency is also examined and an explanation of its cause is proposed.

G. R. TILTON, G. L. DAVIS, AND G. W. WETHERILL (Carnegie Institution of Washington, Washington, D.C.) *The Age of the Baltimore Gneiss*—Zircon and microcline from the Baltimore gneiss near Baltimore give a Precambrian age while biotite from the same rock is dated as Paleozoic. Nearly concordant U-Pb ages for two samples of zircon and the Rb-Sr age of a microcline agree within the limits of error at about 1050 m y. Three samples of biotite have Rb-Sr ages of 305–320 m y, values which agree closely with a biotite K-A age determined by Wasserburg. To specify the history of the gneiss it is necessary to ascertain whether the zircon and microcline could have been detrital in origin. Such a possibility cannot be excluded for the zircon, but petrographic examination indicates that a detrital source for the microcline is improbable. It is believed that the rock crystallized 1050 m y ago and was subjected to metamorphism 305–320 m y ago. The biotite was formed or recrystallized at that time while the zircon and microcline preserved the record of the original age. These measurements extend the known occurrence of 1000 m y -old rocks in the Appalachian region as far south as Maryland. Indication of even further extent of these rocks is given by a biotite from Mary's Rock Tunnel, Shenandoah National Park, that has a Rb-Sr age of 900 m y.

KURT TOMAN (Geophysics Research Directorate, Air Force Cambridge Research Center, 415 Summer St., Boston, Mass.) *A Statistical Relationship between Sunspots and M-Regions*—A cross-correlation technique has been used between the final Zurich sunspot number Z and the planetary K-index ΣK_p. The period from 1940 to 1954 was investigated. One correlation interval contained 180 pairs of successive daily values, running means of 5, 10, 15, and 20. Employing the lag method, correlograms were found to be reasonably smooth, disclosing periodicities as related to the solar rotation and various displacements for optimum correlation. Under the assumption of a predominantly radial solar emission of particles and their constant mean travel time, these displacements were interpreted in terms of a relative longitudinal distribution of sunspots and M-regions.

Robert J. Uffen (Department of Geophysics, University of Western Ontario, London, Ont., Canada) *On the Origin of Rock Magma*—The remarkable correlation between the locations of ocean trenches, eugeosynclines, gravity anomalies, volcanic islands, and earthquake focii suggests a common origin. These phenomena are frequently interpreted as due to compressive failure of the outermost crust of the Earth. So Yoder's (1952) hypothesis has been extended to include remelting upon release of pressure during compressive, rather than tensile, failure. The mean pressure and corresponding melting ranges have been estimated for the materials of the crust, leading to the conclusion that the more basic magmas are generated at the greatest depths. The hypothesis is quantitatively feasible but the data, especially the actual temperature distribution, are inadequately known.

H. J. Van Hook (Department of Geophysics and Geochemistry, College of Mineral Industries, Pennsylvania State University, University Park, Pa.) *A Preliminary Report on the System Ag_2S-Bi_2S_3-PbS*—Liquidus, solidus, and subsolidus phase-equilibrium relations in the binary systems Ag_2S-Bi_2S_3, Ag_2S-PbS, Bi_2S_3-PbS, and $Ag_2S \cdot Bi_2S_3$-PbS are being investigated. The compounds Ag_2S (argentite), Bi_2S_3 (bismuthinite), and $Ag_2S \cdot Bi_2S_3$ (matildite) melt at 834 ± 5°C, and 801 ± 5°C, respectively, 'at the vapor pressure of the system'. A new compound, $Ag_2S \cdot 3Bi_2S_3$, has been synthesized below the solidus. Limits of solid solution between these phases have been determined as a function of temperature. Matildite undergoes a transformation at 180 ± 15°C, the high temperature form being isometric. Matildite and galena are completely miscible at the solidus and a miscibility gap is present at low temperatures. Presumably the low-temperature form of matildite is relatively insoluble in galena and this change of solubility with temperature is responsible for the common occurrence of matildite as an intergrowth with galena.

A. Walton and W. S. Broecker (Lamont Geological Observatory, Columbia University, Palisades, N.Y.) *Recent Results on the Ionium Method of Age Determination*—The Th^{230} (ionium) method has been used to estimate ages and sedimentation rates of deep-ocean sediments. Very few cores analyzed by the radium method have yielded ideal decay curves. The present investigations have been made to determine the reasons for the observed discrepancies. Core A-180-72, collected in the equatorial Atlantic Ocean (lat. 00°35.5′N, long. 21°47′W), has been investigated by total alpha, radon leakage, and radium measurements on various chemically and mechanically separated fractions. The non-carbonate fraction contains the majority of the radium and the results strongly suggest migration of radium. Both radon leakage and acid leaching experiments were used to distinguish between 'migrating' and 'fixed' radium.

The concentration of fixed radium in the non-carbonate fraction shows an approximate three-fold increase at a depth of about 20 cm. This depth marks the midpoint of the change from the relatively cold surface water temperatures of glacial times to the warm temperatures of recent times. C^{14} data indicate that this change occurred at about 11,000 years ago with a corresponding threefold decrease in the deposition rate of the non-carbonate fraction during recent times. The validity of these conclusions is currently being checked by direct Th^{230} measurements.

R. K. Wanless and G. B. Leech (Geological Survey of Canada, Ottawa, Canada) *Lead Isotope Studies of the Sullivan and Other Deposits in the East Kootenay District, Southeastern British Columbia*—The work reported here is part of a continuing program of the Canadian Geological Survey, planned to investigate isotopic variations and their relation to ore genesis and geological phenomena. The deposits studied occur in argillites and quartzites of Late Precambrian age and include the huge Sullivan ore body which is a replacement of certain beds within a single stratigraphic zone. The other deposits are small, and in further contrast, they are localized along fractures unrelated to stratigraphy. To date, 30 lead isotope determinations have been carried out. Of the samples, 21 are from the Sullivan deposit, representing widely separated parts of the ore body and varied mineralogical and structural environments within it. The average Pb^{206}/Pb^{204}, Pb^{207}/Pb^{204}, and Pb^{208}/Pb^{204} ratios determined are 16.66 ± .09, 15.59 ± .05, and 36.39 ± .12 respectively. The maximum variations are Pb^{206}/Pb^{204}, 2.9 pct; Pb^{207}/Pb^{204}, 2.7 pct, and Pb^{208}/Pb^{204}, 1.5 pct. On the other hand, galena specimens from most neighboring small deposits studied, which also occur in Precambrian formations, exhibit higher isotopic ratios than the Sullivan average and show substantial variation within the group. The striking constancy of the isotopic ratios indicates that the Sullivan lead was deposited from a single homogeneous source having a normal uranium-thorium content. The isotopic distribution in most of the smaller deposits, on the other hand, bears no relationship to that found in the Sullivan deposit.

H. W. Wells (Department of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, D. C.) *Ionospheric Focusing at 40 Mc/s*—Signals from the first Soviet satellite (1957 Alpha) at 40.002 Mc/s were monitored at the Derwood (Maryland) Experimental Laboratory of the Carnegie Institution of Washington. The receiving instrument was a Ryle-type phase switching interferometer using folded dipole antennas separated about 12 wave lengths. A movement of any signal source through the antenna pattern produces the well-known interference structure with maxima and minima resulting from the addition or cancellation of the combined signals from the two antennas. The recorder was operated continuously for the collection of propagation data rather than orbital information. The results show the normal series of characteristic interference patterns separated by the 90 minute interval between successive transits. The report includes some conjecture on mechanisms for 'image' formation in the ionosphere and a discussion of other periods of 40 Mc/s interferometer signals when the satellite was well beyond the horizon.

M. Pat Wennekens (Marine Laboratory, University of Miami, Coral Gables, Fla.) *Hydrography of the*

Straits of Florida—The Straits of Florida can be subdivided into three hydrographic provinces: (1) Southern Straits where the hydrography and bathymetry are an integral part of the eastern Gulf of Mexico. Two water masses, Yucatan Water originating from the Carribbean and Continental Edge Water formed in the eastern Gulf merge to form the Florida Current. (2) Cay Sal Region, an area of hydrographic transition. The bathymetry between Cay Sal Bank and the Florida Keys disturbs the direction of flow between the shallow and deep water. Santaren and Nicholas channels are influenced by western Atlantic Water originating from the Old Bahama Channel. (3) Northern Straits where three water masses are observed: Yucatan, Continental Edge, and western Atlantic waters, the latter easily identified from its higher oxygen content. The sill depth of the Straits of Florida lies slightly lower than the average depth of the oxygen minimum being exactly within the average depth of the phosphate maximum.

C. A. Whitten (U. S. Coast and Geodetic Survey, Washington, 25, D.C.) *Distortion in Continental Triangulation*—The present network of triangulation in the United States is the result of adding individual surveys season by season to the existing framework. The last major readjustment of the national net was in 1927. The skeleton framework of that date is now covered by crisscrossing arcs and area nets of first- and modified second-order triangulation. When each survey is mathematically adjusted to be consistent with the previously adjusted surveys, small twists and strains are introduced. These tend to accumulate through successive adjustments to a point where observations are distorted far beyond normal expected errors. Efforts are made to keep this distortion to a minimum by increasing standards of accuracy for the basic framework and by planning surveys to give strength to the net as well as furnishing desired information for engineering and scientific projects. Methods of computation which will give complete information on internal accuracy and checks must be used. Also, through the application of modern electronic computing equipment, it is possible to adjust the maximum size net, thereby reducing probability of extreme distortion.

David E. Willis, Robert C. Fitzpatrick, and J. T. Wilson (University of Michigan Engineering Research Institute, Ann Arbor, Mich.) *Some Observations on the Rainier Underground Nuclear Detonation*—Observations were made using standard low-frequency refraction geophones. The outputs of several configurations of geophones were recorded on magnetic tape. A 5-cps low-pass filter was used to improve signal to noise ratio. The unfiltered output of a single geophone sitting on a concrete pad was fed into a unique seismic level recorder. The output of this was recorded on an Esterline-Angus pen recorder. Level recorder data indicate prominent P, S, L_g, and L_r waves. Analysis of the magnetic tape recorded data indicates frequencies higher than those normally expected to be propagated over long distances.

John W. Winchester (Massachusetts Institute of Technology, Cambridge, Mass.) *Sodium and Potassium Determination by Neutron Activation*—For a wide variety of common rocks and minerals, virtually all of the radioactivity induced by a short thermal neutron irradiation and remaining 48 hours after irradiation is due to sodium and potassium. The active species are 15-hour Na-24 ($E_\beta = 1.4$ Mev, $E_\gamma = 2.75, 1.37$ Mev), and 12.5-hour K-42$_\gamma$ ($E_\beta = 3.5$ Mev, $E_\gamma = 1.5$ Mev present in ten per cent of the decays). By selective β and γ counting the amounts of each active species can be measured separately. It is then possible to determine sodium and potassium in many rocks by pile neutron irradiation of samples and standards followed by counting of the induced radioactivity without prior chemical processing. A test experiment for the determination of potassium in granite, gabbro, shale, clay, feldspar, biotite, muscovite, and lepidolite using a K_2CO_3 reference standard gave potassium contents with a few per cent accuracy by selective β-counting with an end-window proportional counter and aluminum absorbers. The principal source of error was in counting, especially in determining the γ-ray contribution from Na-24 to the total counting rate. Improved counting techniques should lead to much more accurate potassium determinations and the method should be rapid and free from chemical contamination.

J. Lamar Worzel (Lamont Geological Observatory, Columbia University, Palisades, N.Y.) *Gravity Measurements on a Surface Ship with the Graf Sea Gravimeter*—Gravity measurements have been made aboard the surface ship *U.S.S. Compass Island* (EAG 153) with the Graf sea gravimeter mounted on a stabilized platform. On the first cruise a line of submarine gravity measurements was repeated and discrepancies of the order of the navigational errors occurred. Many additional measurements made on subsequent cruises agree satisfactorily where they cross lines of previous submarine measurements. Crossings of our own track give better agreement than crossings of the submarine tracks, due to superior navigation.

It is not yet possible to state in what sea states such gravity measurements can be made since difficulties with the operation of the stable platform have made it indeterminate whether the inadequate operation is due to the stable platform or the gravimeter for the rougher seas. The problem of measuring the Eötvös correction is more severe for a surface ship with larger windage and subject to the larger currents which exist at the sea surface than with a submarine. The location of the observation points remains as one of the most serious difficulties of gravity measurements at sea. Nevertheless, the Graf sea gravimeter shows great promise as an instrument to measure gravity at sea from a surface ship. Whether similar results can be obtained from smaller ships remains to be seen. Tests of this question will be made in the near future.

P. J. Wyllie (Department of Geophysics and Geochemistry, College of Mineral Industries, Pennsylvania State University, University Park, Pa.) *The Fusion of Torridonian Sediments by a Picrite Sill in Soay* (*The Hebrides*)—Progressive thermal metamorphism of Torridonian arkose by a small picrite sill has culminated in extensive fusion. From chemical and modal analyses of a fused xenolith the composition of the liquid developed at the stage of maximum fusion was calculated. For this composition a liquidus *PT* curve was obtained by estimating isobaric liquidus temperatures from data in the system orthoclase-albite-silica-water. Since tridymite crystallized from the liquid the maximum pressure is given by the intersection of the estimated *PT* curve with the experimentally determined *PT* curve for the inversion quartz $\rightleftharpoons$ tridymite (in the presence of water vapor). This provides a minimum estimate of 1025°C for the temperature attained by the liquid. The stage of maximum fusion occurred when crystallization of the picrite was almost completed. By analogy with the Karroo dolerites the picrite intrusion temperature may have been 150°C higher than the maximum temperature of the liquid. A *PT* curve for the picrite intrusion temperature, 150°C higher than the estimated *PT* curve for the liquid, gives a minimum temperature of 1175°C and a maximum of 1460°C (at atmospheric pressure). No independent estimate of pressure is available. The picrite is an ultrabasic rock containing 50 to 60 pct of olivine. Its estimated intrusion temperature is higher than that of many other ultrabasic minor intrusions, and higher than would be expected if the sill were emplaced as a largely crystalline magma.

P. J. Wyllie and O. F. Tuttle (Department of Geophysics and Geochemistry, College of Mineral Industries, Pennsylvania State University, University Park, Pa.) *Hydrothermal Experiments on the Melting Temperatures of Shales*—The partial fusion of many sediments will produce some granitic liquid and it is often assumed that shales are the lowest melting rocks in geosynclinal sections. It has been suggested that all magmatic rocks could be generated by the fusion of different sediments, and Oftedahl (1957) suggested specifically that the fusion of shales at granite contacts could produce basaltic liquids. For these reasons the hydrothermal melting relations of five analyzed shales were investigated. The *PT* curve for the beginning of melting of the shales is only 20°C to 40°C higher than the corresponding curve for granites. At temperatures 150°C higher the shales consist of about 50 pct of liquid. At these temperatures many natural granites would be completely liquid. The granitic composition of the quenched liquid is shown by its refractive index (about 1.504). The *PT* curve for the beginning of melting of basalts in the presence of water vapor lies 150–200°C above the similar *PT* curve for granites and it is unlikely that granite liquids would be superheated to the extent necessary to produce basalt liquid by fusion of shale as suggested by Oftedahl. The temperature and heat source in itself is a formidable problem and, when coupled with the chemical differences between basalts and shales, there is little likelihood that basaltic liquids could be produced at granite contacts by fusion of shale. The fusion of shales over a wide *PT* range will produce liquids of granitic composition but complete or partial fusion will not produce basaltic magmas. The nature of the phase or phases (that is, plagioclase, cordierite, pyroxene, etc.) developed during the melting indicates gross chemical characteristics of shales.

Bernard Zellner and Carl D. Eklund (Tennessee Valley Authority, Knoxville, Tenn.) *Hydrologic Effects of Land Use and Vegetation in the Chestuee and Beech River Watersheds in Tennessee*—In the Chestuee Creek and Beech River watersheds in Tennessee, TVA and other interested Federal, state and local agencies are working with the local people in a program to promote improved land use and management. Assistance to the people seeks increased crop and forest production and efficient utilization of water. The effects of cover and management on water relationship are being measured. Hydrologic records have been kept in the Chestuee Creek watershed since January 1944. Land-use surveys in April 1944 and April 1954 form a basis for comparing vegetative changes with changes in the watershed hydrology, particularly the reduction of sediment loads. Hydrologic measurements in the Beech River watershed began in January 1953. Representative farms were surveyed for land use in 1950, and a comprehensive land-use study was made on one subwatershed in 1954. The information thus obtained will be used as an index to improvements in land management. Experimental research and demonstration on a small watershed in the area have gone on for over 15 years and demonstrate the efficiency of reforestation.

B. D. Zetler, H. B. Stewart, Jr., and C. B. Taylor (U. S. Coast and Geodetic Survey, Washington, D.C.) *Recent Ocean Temperature and Sea-Level Anomalies on the West Coast*—The rise in water temperatures and sea level along the west coast during the past six months is linked to a change in the surface geostrophic winds. The water temperature change results both from reduced upwelling and the resulting reduction in geostrophic current. Lower sea level along the coast is described as maintained at an equilibrium during strong upwelling. Sea level then rises as this equilibrium is upset by the reduction in the northerly component of the winds. Presumably stronger west winds contribute to even higher peaks during early 1958.

Alfred J. Zmuda (Applied Physics Laboratory, Johns Hopkins University, Silver Spring, Md.) *A Method of Analyzing Values of the Scalar Magnetic Intensity*—Various studies on the interaction between charged particles and the geomagnetic field indicate the existence of a source of magnetism located above the Earth's surface. It is likely that for the near future, magnetic studies connected with the external source and with upper-air magnetic properties in general will be conducted primarily with magnetometers measuring only the magnitude of the intensity, not its direction. With this type of data the customary methods of analysis are not applicable. An appropriate analytic method is treated which utilizes a series for the square of the scalar magnetic intensity. The terms of this series are obtained through the use of the series of spherical harmonics generally applied to each component of the intensity. Through an analysis of scalar intensity alone, the method yields the magnetic characteristics that are normally obtainable through a spherical harmonic analysis of the vector magnetic intensity. Also, the variation with altitude of the magnetic equator is treated in conjunction with the location of the equator for cosmic rays.

Abstracts of the papers presented at the Pacific Southwest Regional Meeting, Pasadena, California, February 6–7, 1958, listed in the order of the last name of the first author

CARL S. BENSON (Division of Geological Sciences, California Institute of Technology, Pasadena, Calif.) *Physical Investigations on the Snow and Firn of Northwest Greenland during 1952, 1953, and 1954*—The Greenland Ice Sheet is a single monomineralic rock formation. The bulk of the formation is metamorphic but it is covered by a thin (maximum thickness approximately 85 m or 270 ft) sedimentary veneer of snow and firn. This sedimentary member is perennial above the firn line; and its history may be deciphered by the methods of classical stratigraphy and sedimentation. During a period of three years 118 test sites (82 pits and 85 supplementary ramsonde profiles) were studied along a 300-mi traverse, extending from 2000 to 8000 ft above sea level in northwestern Greenland. Measurements of temperature, density, ramsonde hardness, and grain size were made on the various firn strata at each pit. This work is part of the arctic research program of the Snow, Ice and Permafrost Research Establishment (SIPRE), Corps of Engineers, Wilmette, Illinois.

The following three facies are recognized within the perennial sedimentary firn: (1) The soaked facies which has been completely soaked with water during the melting season. It extends from the firn line to the uppermost limit of complete saturation, the saturation line. (2) The percolation facies which is subjected to localized percolation of melt water from the surface without becoming saturated. It extends from the saturation line upward to the limit of surface melting, or the dry-snow line. (3) The dry snow (firn) facies upon which no melting occurs. It extends from the dry-snow line to the crest of the Greenland Ice Sheet. The saturation line gives rise to discontinuities in temperature, density, and ramsonde data, and may also be located by examination of the strata in pits. It is as sharply defined as the firn line, but the dry-snow line, although determined by the same methods, is more a zone of transition. This percolation can occur in snow or firn of subfreezing temperature. Stratification of firn results from variations in the conditions of deposition and subsequent diagenesis. Summer firn layers have lower density and hardness values and coarser grain size than winter layers; they may also show evidence of surface melt. The onset of fall and early winter is often identified by an abrupt increase in density and hardness together with a decrease in grain size. The identification of seasonal layers gives a measure of annual accumulation. The data indicate that the nourishment of the ice sheet is entirely by cyclonic storms and that precipitation in this region is about five times greater than that recorded at Thule. This difference is only partly a result of local topography. The Thule records are believed to be in error because the standard precipitation gage is not adequate for measuring snow storm precipitation.

FREDERIC A. BERRY (Aerometric Research, Inc., Santa Barbara, Calif.; formerly Advisory Committee on Weather Control, Washington, D.C.) *Results of the Evaluation Program of the Advisory Committee on Weather Control*—The Advisory Committee on Weather Control was established by act of Congress in 1953, and directed to make "a complete study and evaluation of public and private experiments in weather control for the purpose of determining the extent to which the United States should experiment with, engage in, or regulate activities designed to control weather." The Committee, operating with a modest budget and for only a brief period of time, concentrated its efforts on an attempt to evaluate the results of cloudseeding operations using silver iodide smoke generators, both by statistical methods and a program of small-scale field experiments. In its final report, submitted to the President on December 31, 1957, the Committee reported, among other things, that in its opinion the seeding of winter-type storm clouds in mountainous areas of the western United States had produced an average increase in precipitation of 10 to 15 pct from the seeded storms. The Committee recommends the establishment of a long-term research program designed to provide the foundation of fundamental knowledge of the physical and chemical processes in the atmosphere necessary for a more effective practice of weather modification.

MAX BOOKMAN AND LUCIAN J. MEYERS (California Department of Water Resources, Los Angeles, Calif.) *San Diego's Future Water Requirements*—San Diego County is one of the fastest growing areas in the nation. During the decade 1940 to 1950, the population doubled and has now tripled since 1940. It is estimated that the number of people will continue to increase so that in 50 years there may be 2½ million people in San Diego County or three times the present population. Today this area is largely dependent on limited imported water supplies and in view of the potential growth, keeping pace with the accelerated demands for more water is an important major consideration. This presentation depicts the results of a recently completed detailed study made by the California Department of Water Resources of the market demands for water in San Diego County. These studies included projections of probable future population growth; economic studies of the future of irrigated agriculture, industry, and commerce; field studies of land use potentials with reference to adaptability of the land to crops and to urban and suburban developments; studies of the ability to pay for water by crops climatically adapted to the area; and a determination of unit uses of water by urban, suburban, and agricultural entities. The future water requirements for San Diego County were thus determined and the interesting results give an indication of what southern California and the State of California as a whole may expect to face in the immediate future in respect to their requirements for supplemental water supplies.

ROBERT H. BORN (California Department of Water Resources, Los Angeles, Calif.) *Effect of Recent Urbanization on Orange County Water Requirements*—This discussion will present results of recently completed studies by the California Department of Water Resources on the water requirements of Orange County as affected by rapid land use changes and other growth dynamics. Of significant interest are the extensive changes from agricultural development to urban and suburban development which has resulted in greater utilization of both local and imported water supplies. In areas such as Orange County, where expansion and change in the cultural development is accelerated, the periodic evaluation of water utilization is essential for planning future developments required to maintain adequate water supplies and the timing of their construction.

Frederick A. Brooks (University of California, Davis, Calif.) *Remarks on Heat Flow in Sandy Soils*—In spite of difficulties with soil moisture the use of Fourier analysis leads to significant determinations of heat penetration and loss rates in the ground and invites the calculation of the important half-cycle heat storage which depends on an unfamiliar thermal property of the soil, $\sqrt{kC}$, namely the square root of the product of thermal conductivity and volumetric heat capacity. The deep-soil temperature records of Alfred Smith carried out in Davis, California, 1932–1935 have been reinterpreted. These include four years of continuous weekly recordings from 4- to 12-ft depth and the year's record of day and night temperatures from the surface to 36-inch depth. The curves presented have considerable significance for regions of dry summer climate in that, in contrast to the published deep-soil temperatures in Europe, these show very sharp rise in soil temperatures in May following the fully developed winter minimums with no more than occasional, superficial freezing.

Recent work in Holland and Australia on moisture transport in soils now provides theoretical background for laboratory measurements of thermal conductivity of soils such as reported by Kersten, and also for measurements by S. Richards at Riverside of nocturnal moisture loss from the soil which we previously reported as amounting in heat to about ten per cent of the net nocturnal radiation rate. De Vries treats the transport of heat by evaporation and recondensation along a temperature gradient as a pseudo heat conduction which above 60°C exceeds heat conduction by liquid water. The thermal conductivity curves calculated by De Vries for a few of the Kersten samples are presented and also the curve for Yolo light clay soil (from Davis, California) reported by Philip. It is to be noted that by using their coordinate of volume-fraction-of-water it is possible to include on a single graph the thermal conductivity of peat soil in meaningful relation with the conductivities of sandy soils.

Norman H. Brooks (California Institute of Technology, Pasadena, Calif.) *Laboratory Studies of Dunes in Streams*—The hydraulic roughness of alluvial streams depends largely on the configuration of the bed, which may range from being flat to being covered with large dunes. During variable flow conditions the bed pattern and roughness of a given stream may change considerably, and should not be considered constant. Laboratory flume experiments were made to study the behavior of dunes in a bed of fine sand. Dune heights and wave lengths were measured, but it was found that they were not simply related to the observed friction factors. At high velocities the dunes become unstable and the bed is rapidly leveled out. The actual mechanisms of dune growth and movement were studied by means of high-speed and time-lapse motion pictures. A seven-minute film illustrating various features has been prepared for showing at the meeting.

R. H. Burgy and C. R. Pomeroy (Department of Irrigation. University of California, Davis, Calif.) *Interception Losses in Grassy Vegetation*—Interception of precipitation by various vegetative types is an important factor in the disposal of precipitation. Watershed management research to evaluate the effects of modifications of vegetation on the runoff must include more specific information on this important factor than is now available. In view of the paucity of information on this subject a laboratory technique utilizing plants grown in nutrient solution has been developed to accurately evaluate interception losses and related phenomena in grass plots.

Although the intercepted moisture that remains on the vegetative canopy during and at the end of a period of precipitation is subject to evaporation into the atmosphere, it does not necessarily follow that this is a complete loss to the plant, soil, water complex. It was found that in the case of a vigorously growing and transpiring crop the evaporation of a given amount of intercepted precipitation from the leaf surfaces involved was accompanied by a reduction of evapotranspiration in a like amount. The total loss of moisture, when considering the full system of plant, soil and water, was approximately the same in grass plots with both wet and dry leaf surfaces. The interception storage component and precipitation passing through the vegetative canopy as stem flow (S), through fall (T), or drip (D) were measured to determine the relationships and magnitudes. Storage capacities were observed to agree essentially with those reported by other investigators although some variations can occur with different storm types and intensities. S-T-D values were found to be quite significant even at the beginning of small storms.

Stanley N. Davis (Stanford University, Palo Alto, Calif.) *Changes in Salinity in Ground-Water Basins*—Ground water is subject to slow changes of chemical quality particularly within hydrologic basins which have been placed under irrigation. The changes can be expressed by differential equations in which the rate of change of a particular ion concentration is equal to the rate of ion inflow into the basin minus the rate of ion outflow plus or minus the rate of ion precipitation, solution, or exchange. If perfect mixing were to take place, accumulation of most ions would not be harmful in ground-water basins which have significant exterior drainage. Unfortunately perfect mixing is not achieved, and areas of excess salinity are formed in various parts of large basins. Methods of estimating local changes of salinity are presented; however field application awaits the collection of hydrologic and geochemical data of more detail than is presently available.

Hans A. Einstein (University of California, Berkeley, Calif.) and **Huon Li** (University of Pennsylvania, Philadelphia, Pa.) *Why do Secondary Currents Occur in Straight Channels?*—The existence of straight uniform flows without secondary current is studied. It is shown that laminar flows of this kind can remain without secondary currents independent of cross section and velocity distribution. For turbulent flows it is shown that secondary flows will develop spontaneously if in any part of the section the expression for $\frac{\partial \xi}{\partial t}$ as given in Eq. (19) is not vanishing.

GIFFORD C. EWING AND FRED B. PHLEGER (Scripps Institution of Oceanography, La Jolla, Calif.) *Tidal Influence on the Spacing of Inlets into Coastal Lagoons*—A common type of coastal configuration is one in which a long, narrow tidal lagoon of fairly uniform cross section lies parallel to the coast separated from the ocean by a low, sandy barrier island. It is frequently found that the barrier island of this type of lagoon is interrupted by inlets at more or less regular intervals of the order of 15 mi. The hypothesis is developed that this characteristic interval is determined by the variation in the hydraulic head which is developed across the barrier by the phase relation between the tide inside the lagoon and on the outer beach. Supporting evidence is presented based on tidal studies of Santo Domingo Lagoon in the arid region of Baja California.

LLOYD C. FOWLER (California Department of Water Resources, Los Angeles, Calif.; formerly Missouri River Division, Corps of Engineers, Omaha, Nebr.) *A note on the Intriguing Variation in the von Karman Universal Constant in Rivers*—The von Karman universal constant, kappa, in the logarithmic velocity distribution equation has been determined from laboratory experiment with clear water to be close to 0.4. Measurements in both the field and the laboratory of the velocity distributions in sediment laden waters flowing over a movable bed have shown that the value of kappa is less than 0.4. Further, these same measurements indicate that it is not a constant. However, field measurements by the U.S. Army Corps of Engineers of velocity distributions indicate that for large clear water rivers with nonmovable beds, the kappa value is about 0.4.

EDWARD D. GOLDBERG AND ROBERT W. REX (Scripps Institution of Oceanography, La Jolla, Calif.) *Contribution of Airborne Particles to Pelagic Sediments*—The quartz contents of pelagic clays from the eastern Pacific Ocean show a marked latitudinal dependence with a maximum around 30°N. Present evidences indicate that the quartz is mainly transported to the deposits through the atmosphere and that the observed distribution is probably related to the latitudinal values of the atmospheric wind fluxes and exposed arid land areas. A number of sediments display a distinct change in quartz content with depth. In all cases, there is a marked decrease going from the recent to the older strata. It is suggested that the changes indicate a major climatic change that occurred sometime during the Late Tertiary.

G. EARL HARBECK, JR. (U. S. Geological Survey, Denver, Colo.) *Evaporation Suppression—A Progress Report*—Studies of methods of suppressing reservoir evaporation by the use of a monomolecular film were begun in 1956 by the U. S. Geological Survey in cooperation with the Southwest Water Evaporation Research Council of Texas. Approximately 150 chemical compounds were screened in the laboratory by Southwest Research Institute. The most promising of these were tested on a small ranch pond near San Antonio and on a natural lake near Liberty, Texas. Provisional results indicate that evaporation from the ranch pond was reduced 18 pct during a three-week period in October. Further studies are underway at two other reservoirs in Texas. Techniques have been developed for the evaluation of the savings in evaporation by the use of a combination of the energy budget and mass transfer methods for measuring evaporation. The required calibration periods have been completed at these two reservoirs and a film has been applied to one of them.

EVERETT D. HOWE (Division of Mechanical Engineering, University of California, Berkeley, Calif.) *Status of Sea-Water Conversion Research*—The production of fresh water from sea water or other saline sources has been under intensive study in the United States since 1951, when the California Legislature appropriated funds for the University of California to undertake work in this field. The following year a Federal program was set up by Congress and has been administered by the Office of Saline Water in the U. S. Department of the Interior. This office appropriates money for experimentation by colleges, research organizations, industrial firms, and individuals on a contract basis and publishes the results. The office also provides coordination with other countries, as exemplified by the International Symposium held in Washington last November. The paper attempts to summarize not only the progress made in the University of California program but also status of research being done elsewhere.

Research programs have been directed at many different separatory processes since there are several physico-chemical phenomena which may be utilized. The schemes which have received attention include the well-known multi-effect and vapor compression distillation methods, freezing, use of solar heat, osmotic membrane applications, electrolysis, ion exchange, and solvent extraction. The objective of all of the programs is to develop a scheme which will produce fresh water at a price of $100 per acre foot or less, which would be competitive with some municipal sources. Multi-effect distillation and vapor compression distillation are the only two methods which have reached a truly commercial phase at this time, and are both too expensive in their present forms. Radical changes in design and operation of these plants have been proposed which could result in costs sufficiently low to be interesting. Certain pilot plant tests are now under way on these proposals.

Electro-dialysis is presently on a semi-commercial basis in that a number of installations are now operating the largest one being now constructed in South Africa having a capacity of some 3,000,000 gpd. This method seems very promising for demineralizing waters containing about ten per cent of the mineral concentration found in sea water. Freezing methods using the freeze-evaporation principle at low pressures seem to have considerable merit and are being studied by several investigators. The most economical method for separating the ice from the brine is that of counter-current washing. This scheme is still in the glassware laboratory phase. Solvent extraction, osmotic devices, and others to be discussed are still in early stages of development and cannot be accurately evaluated as yet. Developments of the past six years have resulted in a reduction of estimated minimum costs from over $400 per acre foot to slightly more than $100 per acre foot. The next two years should see the firming up of costs for at least five potentially low-cost schemes.

C. E. JACOB (P. O. Box 347, Northridge, Calif.) *Salt-Water Encroachment in Horizontal Confined Aquifers of Uniform Thickness*—The theory of steady states of opposed and parallel flows is outlined. Two simultaneous partial differential equations are obtained by using the method of Dupuit in both salt and fresh-water flows. Nonsteady states of flow are treated by numerical and graphical integration between neighboring steady-state solutions, assuming that a nonsteady flow may be approximated by a continuous succession of steady states. The validity of this approximation is tested. Simultaneous finite difference equations are set up for treatment by electronic analog. The theory is applied to typical coastal ground-water reservoirs. The sketchily known histories of encroachment are recapitulated as closely as possible.

JOHN KNAUSS (Scripps Institution of Oceanography, La Jolla, Calif.) *Variations in the Trade Winds and Changes in the Pacific Equatorial Countercurrent*—Because of the large amount of new observational data on the Pacific Equatorial Countercurrent it is now possible to describe the seasonal and spatial changes in this current with some certainty. The picture of the current that results from this analysis is compared with the structure of the Countercurrent as predicted from different theoretical models which have been proposed. It is shown that the Sverdrup model (1947) provides the best agreement.

BEN E. LOFGREN (Ground Water Branch, U. S. Geological Survey, Sacramento, Calif.) *Near-Surface Land Subsidence in Western San Joaquin Valley, California*—Numerous evidences of land subsidence have been observed on certain lands in the San Joaquin Valley immediately after the application of water. Extensive settlement and soil cracking occur along ditches or where water accumulates in ponds; and irregular, undulating surfaces develop when irrigation is attempted. Detailed experiments are being made on quarter-acre test plots in western Fresno County by the Inter-Agency Committee on Land Subsidence in the San Joaquin Valley. The rate of water infiltration is being measured, as is the rate of subsidence of bench marks located on the surface and at various depths down to 300 ft. As of October 24, 1957, after 385 days of operation of Test Plot B, surface bench marks had settled an average of 8.77 ft; the bench mark at a 25-ft depth had settled 7.95 ft; the 50-ft bench mark, 6.63 ft; the 75-ft bench mark, 4.87 ft; and the 100-ft bench mark, 2.82 ft. The 150-ft bench mark had not yet registered a movement; however, settlement at this depth is anticipated soon. Infiltration at a continuing rate of 0.25 ft of water per day has been more than sufficient to fill the pore space beneath the test plot to the wetted depth, indicating that considerable lateral spreading of the water has occurred. Cored samples collected before and during the spreading operation show the increase in density and moisture content to a depth of 120 ft. The low density of the alluvial sediments and their extreme dryness apparently are two important factors in the land subsidence resulting from application of water in the area.

ROBERT A. MERRIAM AND EVERETT L. HAMILTON (California Forest and Range Experiment Station, U. S. Forest Service—California Division of Forestry, Glendora, Calif.) *Effects of Fire on Streamflow in Grass Woodland Watersheds in the Central Sierra*—Several gaged small watersheds of about 25 ac in the woodland-grass range land of the Sierra Nevada foothills were burned in a summer wildfire in 1951. Streamflow characteristics during two years following the fire are compared with those during a pre-fire calibration period. Storm peak discharges were related statistically to rainfall quantity and rate variables by multiple correlation analyses. No effect of the fire on storm peak discharge was detected. Total streamflow yield during the first post-fire year, as well as summer spring flow from one watershed, were similar to two pre-fire years with comparable rainfall. No measurable sediment was deposited in the debris basins following the fire. The reasons for the lack of effect of this fire on streamflow are the failure of the fire to consume the woody vegetation, the herbaceous ground cover or the mulch on the soil surface, and the rapid regrowth of annual herbaceous plants.

SETH B. NICHOLSON (Mount Wilson Observatory, CIW, and Palomar Observatory, CIT, Pasadena, Calif.) and OLIVER R. WULF (U. S. Weather Bureau, CIT, Pasadena, Calif.) *The Diurnal Variation of Irregular Geomagnetic Fluctuations*—The diurnal variation of irregular geomagnetic fluctuations has been studied using the eight daily values of the three-hour-range index K of geomagnetic disturbance for nine years from six observatories in moderately low latitudes and fairly well distributed in longitude. Data for days of different degrees of disturbance have been studied separately. A local-time variation and also a univeral-time variation of disturbance appear to be present. In contrast to the local-time component, the universal-time component exhibits a pronounced annual change. In an attempt to account for characteristics of these components it is suggested that a part of geomagnetic disturbance may arise by dynamo action from air motions in the ionosphere that may be related to the large-scale atmospheric circulation.

J. T. O'BRIEN AND D. I. KUCHENREUTHER (U. S. Naval Civil Engineering Research and Evaluation Laboratory, Port Hueneme, Calif.) *Waves in and around Port Hueneme, California, Associated with the Tsunami of March 9, 1957*—The tsunami, generated by a submarine earthquake off Adak, Alaska (N50.2, W170.7), was noticed first in Port Hueneme and in the ocean near it at 12h 59m Pacific Standard Time, March 9, 1957, and persisted until about 16h PST, March 12, 1957. Simultaneous measurements of wave height were made by means of a bottom pressure pickup in the ocean and a surface float housed in a well in the harbor. Most significant components had periods of about 12.5 minutes and 6.0 minutes with the former magnified considerably in the harbor. An average of 29 hourly readings indicates water level changes of 0.53 ft in ocean and 1.74 ft in harbor, both with half periods of about 6.4 minutes. The magnification in harbor does not seem to be explained on basis of excitation of the harbor or any of its basins; it is speculated that it may be explained by oscillations in the submarine canyon fronting the harbor or sub-harmonic oscillation in the harbor basin. No damage was sustained by Mugu-Hueneme beaches or by Port Hueneme or the ships berthed therein.

GUNNAR I. RODEN (Scripps Institution of Oceanography, La Jolla, Calif.) *On a Relation between Atmospheric Pressure and Sea-Surface Temperature in the North Pacific Ocean*—Nonseasonal pressure and temperature anomalies in the north Pacific Ocean occur on a large scale and cover thousands of nautical miles. There exists a relation between the pressure and temperature anomalies. Changes in the general circulation of the atmosphere are held responsible for a significant part of the variation in sea surface temperatures.

HERBERT B. SCHULTZ (Department of Agricultural Engineering, University of California, Davis, Calif.) *Nocturnal Ground Inversions in Southern California in Winter*—The subsidence inversions in Southern California have been thoroughly analyzed by M. Neilburger and co-workers for the summer months in connection with air pollution problems. The present study of radiosoundings in winter revealed a strong influence of free air subsidence on night temperatures above citrus tree tops. In such conditions, wind machines installed at heights between 30 and 40 ft above ground for winter frost protection are embedded in 10 to 20°F warmer air than the orchards underneath. For a period of 10 years of soundings at Santa Maria, California, and Medford, Oregon, the frequency of the strong subsidence inversions in the lower layers showed a maximum during the winter months followed by a quick decline in the spring. (Similar results were obtained by Herath in a statistical analysis of 25 years of kite soundings at Lindenberg, Germany.) This decline may partly explain the inferior performance of wind machines when used for spring frost protection. Furthermore, the frequent winter subsidence warming over the Southern California citrus areas is magnified by the occurrence of orographic subsidence at night caused by gravity flow. Downslope wind profiles in the Riverside area were observed along a 120-ft mast with sensitive anemometers. Precision recording permitted evaluation of velocity in tenths of a foot per second in time intervals of seconds which showed high variability in time and height. However, the dense foliage of the citrus trees (evergreen) opposes this drainage flow keeping cold air trapped inside the orchard. Therefore, the success of wind machines in winter in Southern California must be ascribed largely to the peculiarity of the combined action of microclimatic and aerological conditions.

GEORGE SHUMWAY (U. S. Navy Electronics Laboratory, San Diego, Calif.) *Acoustic, Geologic, and Physical Properties of a Suite of Arctic Slope Sediments*—Six cores were taken from the continental slope in the Arctic Ocean north of the Coleville River delta in depths ranging from 174 m to 2780 m. As depth increases the sediments become finer and, as the following table shows, a number of other sediment properties change in a regular manner. Sound velocity and attenuation measurements were made by a resonant technique. Static shear strength measurements were made by D. G. Moore with a vane shear apparatus. The cores were collected by M. A. Beal and J. H. Sherman III from USS *Staten Island*.

L. H. STOLZY, L. V. WEEKS, T. E. SZUZSKIEWICZ, AND G. A. CAHOON (Dept. of Irrigation and Soils, University of California, Riverside, Calif.) *Estimating Soil Suction from Neutron Measurements*—Soil water may be evaluated from two different aspects. One aspect commonly reported in hydrology, engineering, and evapotranspiration studies is mass transfer of water. The other aspect common to agronomists and horticulturists is water availability or soil suction. The equipment and methods used to measure each are different. It is often desirable to estimate soil suction from moisture content data. The neutron method is a practical approach to measuring moisture by volume (Pv) in soil profiles. However, in soil profiles moisture per cent cannot be evaluated directly in terms of soil suction. Tensiometers are used to measure soil suction in the field up to 0.8 bar.

It was the purpose of this study to determine soil suction–soil moisture per cent relationships from data taken with tensiometers and neutron equipment under field conditions. These data were also compared to soil suction–soil moisture content data obtained with pressure membrane and pressure plate equipment in the laboratory. Soil suction–soil moisture relationships calculated from data obtained from sandy loam soil packed in large cylinders were not significantly different within cylinders by depths but were different between cylinders. Laboratory determinations of per cent moisture (Pv) at 150 and 330 millibars showed good agreement with the suction-moisture curves from the cylinders. Moisture values measured in the laboratory at 100 and 1000 mb were 23.1 and 8.5 pct respectively. By comparison the ranges of suction values calculated from the cylinder data at the 95 pct confidence interval were as follows: 21 to 23 mb when Pv was 23.1 pct and 540 to 600 mb when Pv was 8.5 pct. Suction-moisture relationships in the field at different locations and depths were significantly different in some cases with the greatest differences occurring at the three-ft depth. Coefficients of correlations for each location and depth varied from −0.95 to −0.99. However, when data from four locations were combined the following correlations were obtained: one-ft depth −0.97 two-ft depth −0.91; and three-ft depth −0.81. This would show that in uniform soil one suction–moisture relationship may represent only a given area. If differences do occur in the profile it may be necessary to make a separate calibration for each depth and location.

RICHARD B. TIBBY (Allan Hancock Foundation, University of Southern California, Los Angeles, Calif.) AND CHARLES G. GUNNERSON (Bureau of Sanitation, City of Los Angeles, Calif.) *Studies on Eddy Diffusion in Santa Monica Bay, California*—Early studies of mixing processes in the sea showed that the coefficient

(Table for Shumway Abstract on p. 542)

Location Lat. Long.	Water depth	Median dia.	Sorting σ_ϕ	Wet density	Porosity	Compr. sound. velocity	Attenuation	Static shear strength
	m	mm		g/cm³	pct	km/s	db/ft	lb/in²
71°08′ 150°24′	174	0.0173	2.85	1.67	60.4	1.551 (26.4°C)	7.14 at 31.3 kc/s	17.03
71°08′ 150°24′	232	0.0114	2.82	1.55	67.1	1.521 (26.8°C)	1.69 at 31.0 kc/s	...
71°10′ 150°24′	439	0.0058	2.6	1.41	76.4	1.493 (26.8°C)	0.95 at 30.3 kc/s	11.02
71°11′ 149°54′	1024	0.0038	2.4	1.32	81.2	1.491 (25.7°C)	1.34 at 30.2 kc/s	3.16
71°29′ 149°39′	2203	0.0025	...	1.305	82.6	1.486 (25.0°C)	0.94 at 30.3 kc/s	...
71°46′ 148°41′	2780	0.0019	2.1	1.306	83.4	1.486 (26.2°C)	0.64 at 30.2 kc/s	4.9

of horizontal eddy diffusivity was extremely large, that vertical mixing was relatively unimportant, that there was no apparent correlation with net current velocity and that the magnitude of the coefficient varied with the scale of the phenomenon. More recently the view has been expressed that the rate of horizontal diffusion basically is a function of particle separation rather than of time or distance from the source and that the coefficient varies with particle separation according to the 4/3 law. Studies on horizontal eddy diffusion were made in Santa Monica Bay, California, where dye streams, current cross pairs, drift cards and the dispersal of sewage gave values from 1.7×10^2 to 2.0×10^6 cm²/sec for distance scales of 27 m to 20 km. The values approximately followed the 4/3 law and were consistent with those found by other investigators and methods. Engineering applications of these data include the spacing of discharge ports in a submarine sewer outfall prediction of the probable width of the sewage field at its intersection with the shoreline.

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Notes and Personalia

Notes

Plans For Extended Abstracting and Indexing Services—A conference was held in Philadelphia, January 29–31, 1958, called by *Biological Abstracts*, under the sponsorship of the National Science Foundation, to consider the needs and problems of abstracting and indexing the world's scientific literature. Representatives of the various abstracting services, such as *Chemical Abstracts*, *Psychological Abstracts*, as well as representatives of fields in which there is now no substantial abstracting service, were present. Six working groups devoted a day to studying individual problems and preparing reports on these problems, following which, at the general sessions, an integrated report was prepared. It was agreed that there should be organized a National Federation of Scientific Abstracting and Indexing Service to integrate the work already in progress and to see to it that the abstract activities are extended appropriately to fields of science not now adequately covered. It was noted that some 500,000 scientific abstracts per year are now covered by the various services, but that there are perhaps on the order of 2,000,000 papers and publications that should be covered. Operating on an extended basis, this endeavor might cost on the order of $20,000,000 a year. In geophysics, it was estimated that there are perhaps 12,000 items per year that should be covered, 3000 of which are now included in *Meterological Abstracts* and about 1000 additional in *Geophysical Abstracts*. Steps have been taken to study this matter on behalf of geophysics by a sub-committee of the Board of Russian Translations, the subcommittee under the chairmanship of Werner A. Baum of Florida State University.

New Publication of the Royal Astronomical Society—The Royal Astronomical Society began the issuance of the *Geophysical Journal*, incorporating the Geophysical Supplement to the Monthly Notices of the R. A. S., Volume 1, Number 1, bearing the date March 1958. It is the plan to publish this as a quarterly. The first number contained nine papers plus a 16-page report on the Eleventh General Assembly of the International Union of Geodesy and Geophysics, held in Toronto, September, 1957. The papers are listed in the bibliography in the current issue of the *Transactions*. There are one falling under a General heading, one under Geodesy, four under Seismology, one in Geomagnetism and Aeronomy, and two in Tectonophysics.

New Publication of the Institute of Physics—*The Physics of Fluids*, under the editorship of François Frenkiel, began publication with the first bimonthly number dated January-February, 1958. This contains seven papers covering various phases of the field.

New Egyptian Publications in Geology—Volume 1, Number 1, of the *Egyptian Journal of Geology*, issued by the Geological Society of Egypt and dated 1957, has recently arrived. The first number contains four papers in English, only one of which, "On the Serial Character of Igneous Rocks," by A. Rittman, bears heavily on geophysics. The Science Council has issued Volume 1 of *Egyptian Reviews of Science*, the first being a review of Egyptian Geology.

New Publication of the British Glaciological Society—Number 1 of *Ice News Bulletin* of the British Glaciological Society dated January, 1958, covers items of current news concerning activities in the study of glaciers and related phenomena.

Ninth Pacific Science Congress—The Ninth Pacific Science Congress, covering the full spectrum of science, was held in Bangkok, Thailand, November 18–December 9, 1957. Five hundred and seventy-five persons attended the Congress. In geophysics, the chief matters of concern related to seismology, meteorology, and oceanography. Further details may be secured from the Pacific Science Association, Bishop Museum, Honolulu 17, Hawaii.

Seventh National Clay Conference—The Seventh National Clay Conference will be held in Washington, D. C., October 20–23, 1958. Interested persons should get into touch with John G. Cady, Program Chairman, Soil Survey Laboratory, Plant Industry Station, U. S. Dept. of Agriculture, Beltsville, Maryland, or H. F. McMurdie, Chairman, at the National Bureau of Standards.

International Oceanographic Congress—This Congress, sponsored by the American Association for the Advancement of Science in connection with the Special Committee on Oceanic Research, ICSU, and UNESCO, will be held at the United Nations Building in New York, August 30–September 12, 1959. Persons who are interested in this matter should get into touch with the Chairman of the Committee on Arrangements, Mary Sears, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts.

Meeting of the Advisory Committee on Arid Zone Research—The Thirteenth Session of the Advisory Committee on Arid Zone Research of UNESCO was held in Karachi, Pakistan, in November, 1957, with E. S. Hills as Chairman for the Session. Forty recommendations were made covering all phases of the Committee's activities from laboratory and field studies to the fellowship program. Attending from the United States was C. W. Thornthwaite, Director, Laboratory of Climatology of Elmer, New Jersey. The Fourteenth Session will be held in Teheran in October, 1958. Interested persons may secure further details by writing to the Committee, c/o UNESCO in Paris.

Immigration of Professional Workers to the United States—Studies of the National Science Foundation indicate that 60,000 immigrants classified as professional, technical, and kindred workers entered the United States on a permanent basis during the four years from July, 1952 to July, 1956, and constitute about six per cent of those immigrating to the United States in those years. Copies of the report can be obtained from the National Science Foundation, Washington 25, D. C.

National Science Foundation Survey of Industrial Research and Development Costs—This survey, which is the third in a series going back to 1953, is sponsored by the National Science Foundation but will in fact be conducted by the Bureau of the Census to compare research and development statistics with other economic data from industrial concerns. Previous studies have indicated that almost three-fourths of the total research and development effort has been provided by industry and that there is good reason to believe that rapid economic growth of some industries has been importantly related to increased investment in research and development.

New Report of the National Science Foundation—The National Science Foundation has recently released a report entitled "Government-University Relationships in Scientific Research and Development." Several recommendations are offered, among these being the need for continuity of support and the need for the Federal agencies to have legal authority to give the institutions title to research equipment procured with the grant or contract funds needed for the work. Copies may be secured from the Superintendent of Documents, Washington 25, D.C., for forty cents.

NATIONAL SCIENCE FOUNDATION FELLOWSHIPS IN SCIENCE FOR 1958–1959—The NSF has announced in March the names of the recipients of 756 predoctoral graduate fellowships for the academic year 1958–1959. These were selected from 3804 applicants. Also announced were the names of 85 winners of regular postdoctoral fellowships (these not including the senior postdoctoral and science-faculty fellowships). Included in the number were 45 in the Earth sciences, 92 in mathematics, 93 in engineering sciences, 158 in chemistry, five in agriculture, and five in astronomy. Of the predoctoral fellowships, 186 were made to first-year graduate students and 196 to terminal-year predoctoral candidate students. The list included 442 who held fellowships during the current academic year. Also announced were about 100 senior postdoctoral and science faculty fellowships.

In April, announcement was made of 525 additional scholarships, 328 in the predoctoral program, 41 in the regular postdoctoral fellowships, 29 senior postdoctoral fellowships, and 127 science faculty fellowships. Details can be secured by writing to the National Science Foundation, Washington 25, D. C.

FELLOWSHIP PROGRAM, ORGANIZATION OF AMERICAN STATES—A new fellowship program will offer grants for advanced study or research to specialists throughout the Western Hemisphere. It is the plan to establish 170 fellowships for the year 1958–1959, with about 500 annually in future years. It is anticipated that grants will be made for periods ranging from three months to two years and will cover such things as travel, fees, work materials, and board and room. Interested persons should address the Technical Secretary, OAS Fellowship Program, Pan American Union, Washington 6, D. C.

NEWSLETTER OF THE INTERNATIONAL ASSOCIATION OF HYDROLOGY—The Association of Hydrology is now publishing a Newsletter distributed without charge to interested persons. This includes activities of the Association as such and also activities of organizations working in related fields as, for example, the World Meteorological Organization. Interested persons should write to Professor L. J. Tison, General Secretary, 61 rue des Ronces, Gentbrugge, Belgium.

DATA REDUCTION OFFICES FOR IGY—The University of Wisconsin and Ohio State University have been given assignments to establish offices to conduct data reduction. The activity at the University of Wisconsin will cover gravity, magnetic, and seismic observations being made by American parties in the Antarctic. The work at the University of Wisconsin will be done under the direction of George P. Woollard. The work at Ohio State will cover glaciological data and will be coordinated with the work of the University of Innsbruck on solar radiation and work at the University of Michigan on ice shelf deformation. The work at Ohio State will be under the direction of Richard Goldthwait.

CONTINUING STATIONS IN THE ANTARCTIC—The Governments of Australia and the United States have agreed to cooperate in maintaining operations at Wilkes Station in the Antarctic for an indefinite period beyond December 31, 1958, the nominal terminal date of the IGY activity. Scientists from both countries will participate in the research activities.

NEW STUDY OF WINDS IN THE UPPER ATMOSPHERE—With the use of rockets which release aluminum chaff more than 50 miles above the Earth, scientists of the Army Signal Engineering Laboratories at Fort Monmouth, New Jersey, are plotting winds in the upper atmosphere. The chaff is released in clouds and is tracked by radar to produce an accurate wind profile as the chaff is swept along by the winds. Continuous measurements have been secured from a height of 283,000 feet down to levels of less than 100,000 feet. Hans J. aufm Kampe and Dudley E. Cline are the ones who are developing this new technique.

GEOTHERMAL POWER DEVELOPMENT IN CALIFORNIA—Work is under way on the first development of geothermal power in the United States. This is in the area of Big Geysers north of Santa Rosa, California, and is being undertaken by the Thermal Power Company.

OCEANOGRAPHIC CRUISE IN THE GULF OF MEXICO, THE CARIBBEAN SEA, AND ADJACENT ATLANTIC WATERS—The Department of Oceanography of the A and M College of Texas has under way an oceanographic survey in areas ranging from Galveston, from which departure took place on May 12, to Bermuda, conducting measurements in temperature, gravity, conductivity, dissolved oxygen, CO_2, chlorinity, alkalinity, phosphorus, and other chemical constituents. Large samples are to be taken from great depths for C-14 determinations.

NUCLEAR REACTOR TO BE USED IN EXPERIMENTS IN ARTIFICIAL PRECIPITATION—The seeding of the steam cloud from Argonne National Laboratory experimental boiling water reactor by silver iodide is being undertaken by a team of scientists under the direction of Roscoe R. Braham, Jr. These experiments are definitely of a laboratory character as compared with the usual field experiments which thus far have been inconclusive. Glass slides with plastic material are placed at various distances downwind and the slides are subsequently examined in the laboratory to see if the ice crystal replicas contain silver iodide particles in the optical center which would indicate that the silver iodide is associated with the nuclear process.

NEW GLACIOLOGICAL MAP OF CANADA—A new map, 63 x 51 inches, has recently been prepared by the Geophysics Laboratory of the University of Toronto and published by the Geological Association of Canada, Room 703, 111 St. Clair Avenue West, Toronto 7, Ontario, Canada. The price is $2.00 (students, $1.00).

GRANT TO IMPROVE INSTRUCTION IN MATHEMATICS IN SECONDARY SCHOOLS—The National Science Foundation has made a grant of $100,000 to Yale University to initiate the work of the School Mathematics Study Group in an effort to improve instruction in mathematics in secondary schools.

WATERSHED MANAGEMENT PROGRAM—The Colorado State University has recently received a grant of $50,000 to aid in the establishment of a full-fledged instruction and research program on watershed management.

NEW COURSE IN GROUND-WATER GEOLOGY—The New Mexico Institute of Mining and Technology announces a program of special graduate courses in ground-water hydrology to start in the academic year 1958–1959. The work will be under the direction of Mahdi S. Hantush, on leave from his post as Dean of the College of Engineering of the University of Baghdad, who has previously devoted six years of study and research as an exchange visitor in the United States. Research facilities are available and a number of assistantships paying $1700 for the academic year will be available. Inquiries should be addressed to E. J. Workman, President, New Mexico Institute of Mining and Technology, Socorro, New Mexico.

TWENTY YEARS OF RESEARCH WORK BY MAGNOLIA PETROLEUM COMPANY—In March, the Magnolia Petroleum Company observed the twentieth birthday of their scientific laboratories, which have expanded from a one-man staff to the present staff of about 380, occupying 25 buildings on a 144-acre tract near Dallas. Over 200 patents on the laboratory's work have been taken out since World War II, and 100 more are pending. Their Marine Sonoprobe, developed by Magnolia and used extensively by Fairchild Aerial Surveys, is used for offshore oil exploration but has also been used to map the bottom of Maine's Passamaquoddy Bay and for other purposes.

Personalia

LESLIE F. BAILEY of the U. S. Coast and Geodetic Survey has received the Meritorious Service Award of the U. S. Coast and Geodetic Survey for his advances in the field of seismology.

GORDON D. CARTWRIGHT, Meteorologist with the U. S. Weather Bureau, has returned after spending 14 months at the Soviet Antarctic IGY station at Mirny in connection with work of the International Geophysical Year. He is the only American stationed at this Russian base and reports that he found the Russian scientists warm, hospitable, and with broad scientific and cultural backgrounds. He took hundreds of cloud photographs and several thousand feet of time-lapse color pictures of special cloud developments.

GILBERT DEWART has recently returned from Wilkes Station in the Antarctic where he spent a year as the station seismologist.

LINDSAY P. DISNEY, Assistant Chief, Tides and Currents Division, U. S. Coast and Geodetic Survey, has been given the Longevity Award for his long years of faithful service in the U. S. Coast and Geodetic Survey.

ALFRED B. FOCKE, formerly the Director of the Marine Physical Laboratory of the University of California at San Diego, has been named Chief Scientist of the U. S. Naval Air Missile Test Center, Point Mugu, California.

JOHN W. GRAHAM, formerly a member of the scientific staff of the Department of Terrestrial Magnetism at the Carnegie Institution of Washington, is now Research Associate in Geology at Woods Hole Oceanographic Institution.

EARL INGERSON, Chief of the Petrology and Geochemistry Branch of the U. S. Geological Survey, has accepted an appointment as Professor of Geology at the University of Texas in September, 1958.

SERGE A. KORFF, Professor of Physics at New York University, has been designated Professor Honorario en Radiacion Cosmica of the Chacaltaya Laboratory of Cosmic Physics of the Universidad Mayor de San Andres in La Paz, Bolivia.

DANIEL LINEHAN, Head of the Geophysics Department at Boston College and Director of the Weston Seismic Station, who has just returned from three months in the Antarctic, has been presented the Insignis Medal of Fordham University. This medal, the award of which honors the zeal of Saint Ignatius of Loyola, founder of the Jesuit Order, is given to Roman Catholic leaders for extraordinary distinction in the service of God through achievement in their professions. A number of years ago he made some extraordinary seismic explorations under Saint Peter's Cathedral in Rome, locating important archaeological finds relating to the early days of the Christian era.

ROBERT R. MCMATH of the McMath-Hulbert Observatory, University of Michigan, has recently been named a member of the National Academy of Sciences.

HOWARD T. ORVILLE, Captain, U. S. Navy, retired, where he was Chief Aerologist, has left his work with the Friez Division of Bendix Aviation Corporation and taken up duties as Vice President of Beckman and Whitley, Inc., San Carlos, California. He will work especially with the Instrument and Missile Products Division in long-range scientific and technical planning.

FRANK PRESS, Professor of Geophysics and Director of the Seismological Laboratory, California Institute of Technology, has recently been elected a member of the National Academy of Sciences.

PAUL A. RECHARD, formerly Director of Water Resources and Commissioner of Interstate Streams for the State of Wyoming, has accepted a position as Senior Engineer for the Upper Colorado River Commission with headquarters in Salt Lake City.

ALFRED C. REDFIELD, Associate Director, Woods Hole Oceanographic Institution, has recently been elected a member of the National Academy of Sciences.

RITA C. SAGALYN of the Air Force Cambridge Research Center was selected to give the Guenter Loeser Memorial Lecture for 1958. The lecture was delivered in the Charter Room of the New England Mutual Building in Boston on June 4. The title of Mrs. Sagalyn's address was "Recent Investigations of Electrical Phenomena in the Atmosphere."

PAUL A. SIPLE, Scientific Advisor and Chief of Research and Development of the Department of the Army, has recently been given the Distinguished Civilian Service Award by the Department of the Army for significant contributions to the scientific knowledge of the Antarctic. He has also recently been awarded the Hubbard Medal, which is the highest honor of the National Geographic Society.

PAUL WEAVER, Professor of Geology at Texas A and M College, has been awarded the Sidney Powers Memorial Medal of the American Association of Petroleum Geologists in recognition of his outstanding contributions to petroleum geology.

WARREN S. WOOSTER has returned to his duties as Associate Research Oceanographer at Scripps Institution of Oceanography after devoting a year as Director of Investigations of the Peruvian Council of Hydrobiological Investigations.

HATTEN S. YODER, JR., Petrologist of the Geophysical Laboratory, Carnegie Institution of Washington, has recently been elected a member of the National Academy of Sciences.

Willis Isbister Milham, Professor Emeritus in Astronomy of Williams College, died March 23, 1957, at the age of 83. He was born at Kinderhook, New York, took his baccalaureate degree from Williams College in 1894 and his master's degree in 1895. He took his doctorate from the University of Strassburg in 1901 and was awarded an honorary doctorate by Williams College in 1946. He entered upon his teaching duties as an Assistant in Physics at Williams College in 1895, and had continued through his career at his alma mater. He became Emeritus Professor in 1942. He had been a member of AGU since 1934.

Peter H. Ottosen, Colonel, U. S. Army, retired, and an associate of the Scripps Institution of Oceanography since 1946, died March 31, 1958, at the age of 72. He was born at Badger, Iowa, and took his baccalaureate degree from Iowa State College in 1908, subsequently doing graduate work at Massachusetts Institute of Technology. From 1908 until 1945, he was a commissioned officer in the Artillery, part of his work being devoted to amphibious training operations. This interested him in oceanographic work. He did research work on the tides and took part in the installation of tide gages at Point Barrow, Alaska, in 1956. He had been a member of AGU since 1946.

Hüseyin Pektas, Head of Fisheries Hydrography of the Fisheries Research Center at the University of Istanbul, died June 11, 1957, at the age of 39. He was born on the island of Cyprus and received his degree from the University of Istanbul in 1940 and his doctorate from Leeds University in England in 1947. He became a member of AGU in 1956.

Union, Section, and Committee Activities

Thirty-Ninth Annual Meeting (1958)

Minutes, General Assembly and Section Meetings

Smoker

The Smoker was held in the Ball Room of the National Press Club, National Press Building, 14th and F Streets, N.W., Washington, D. C., on the evening of Monday, May 5, 1958. There were about 350 in attendance. The gathering was entirely informal and served to provide a pleasant opportunity for those in attendance to greet old friends and meet new ones, and to form ever-changing small discussion groups.

Symposium on Satellite Geophysical Studies

This Symposium was arranged by N. C. Gerson and held in the Great Hall of the National Academy of Sciences on the afternoon of May 6, 1958, John P. Hagen presiding. The session opened at 14h 00m and adjourned at 17n 20m. There were about 275 in attendance. The program, which included discussion from the floor, follows. Abstracts of most of the papers of this and other program papers are to be found in the Reviews and Abstracts of this issue of the *Transactions*.

(1) Lloyd V. Berkner: The IGY and Satellite Vehicles
(2) M. Dubin: Measurements of Meteoritic Impacts on Explorer I
(3) R. A. Minzner: Atmospheric Density from Recent Rocket and Satellite Measurements
(4) G. F. Schilling and T. E. Sterne: Temperatures and Densities Inferred from Observations of USSR Satellites
(5) R. Jastrow and I. Harris: Upper Atmosphere Properties from Minitrack Observations on 1957 α 2
(6) G. W. Swenson, Jr.: Ionosphere Research Using Earth Satellites
(7) H. W. Wells: Ionospheric Focusing at 40 Mc/s
(8) C. Y. Johnson, E. B. Meadows, and J. E. Holmes: Ion Composition of the Arctic Ionosphere

Evening Session

Preceding the Evening Session, there was a subscription dinner at the Statler Hotel in honor of the Bowie Medal recipient attended by about 50 persons including the Minister from The Netherlands, Baron S. G. M. van Voorst tot Voorst, and the Science Attache, J. C. Diels.

The Evening Session was called to order by Vice President L. V. Berkner at 20h 30m, Tuesday, May 6, 1958, in the Lecture Room of the National Academy of Sciences, Washington, D. C. About 200 were in attendance. After appropriate welcoming remarks, Vice President Berkner called on Walter H. Bucher, Chairman of the William Bowie Medal Committee, who cited Johannes Theodoor Thijsse of The Netherlands as the Twentieth Recipient in accordance with the remarks set forth on the opening pages of this issue. Vice President Berkner then made the presentation, and the recipient indicated acceptance in his response, and addressed the assembled group on the subject, In the Borderland between Geophysics and Engineering. At the close of his address a social hour with refreshments was held in the Great Hall of the National Academy of Sciences.

General Assembly: Papers on Frontiers in Geophysics, and Business Meeting

The General Assembly was called to order by Vice President Lloyd V. Berkner at 14h 00m, Wednesday, May 7, 1958, in the Great Hall of the National Academy of Sciences. About 250 were in attendance. Vice President Berkner called on Philip H. Abelson (Chairman, Committee on Meetings, who arranged the program) to act as Chairman and introduce the speakers. The program presented was as follows:

(9) J. A. SIMPSON: Solar-Geophysical Aspects of Cosmic-Radiation Phenomena

(10) FRANCIS BIRCH: Composition of the Crust and Upper Mantle in the Light of Experimental Studies of Wave Velocities in Rocks

(11) ROGER R. REVELLE: The Downwind Expedition to the Southeast Pacific

Upon completion of the session, the chair was returned to Vice President Berkner. Following a brief intermission, the Business Meeting was called to order at 16h 17m.

The minutes of the Business Meeting of the 38th Annual Meeting [see *Trans.*, 38, 438–439, 1957] were approved.

Summary Report of the General Secretary

General Secretary Sayre made a summary report outlining items covered in more detail in the reported minutes of the Executive Committee meetings. He pointed out that during the current year a substantial deficit will occur, caused largely by the greatly increased cost of printing the *Transactions*. Accordingly, the Executive Committee has reluctantly decided that dues for 1959 must be $10.00.

With regard to membership, there are still many qualified persons who are not now members and who should be. The individual assistance of members is needed in bringing these into membership. A directory appears in the April 1957 issue, which should be of help in telling who are members. Application forms appear in the *Transactions* from time to time. We are also seeking more corporation members. A summary of the membership since the last Annual Meeting is as follows:

Membership as of April 25, 1957........	4980	
Reactivated..........................	7	
New members (including 69 applications now being processed)................	503	5490
Resigned	129	
Inactive............................	8	
Dropped (tentatively dropped 148)......	311	
Deceased............................	34	482
Membership as of April 21, 1958....		5008

He noted that the names of 34 members whose deaths had been reported in the last year are cited in the reports of meetings of the Executive Committee and in the brief obituaries carried in the news items in the *Transactions.*

The *Transactions* have been published bimonthly, sometimes a little late. We need more advertising, and the help of members on this is solicited. The Executive Committee, at its meeting May 4, 1958, laid plans for the future development of our publications that will be sent to the entire membership around the late spring or early summer.

Plans have been completed for the publication of Geophysical Monograph No. 2 on the Symposium on the IGY which was held in Washington at the time of the opening of the IGY in July 1957, and tentative plans are under way for the issuance of Geophysical Monograph No. 3 relating to a Conference on Atmospheric Chemistry of the Compounds of Chlorine and Sulphur.

The Russian translation project has been moving slowly. Numbers 1 and 2 of *Izvestiia* (Geophysics Series) have now been released. The quality of translations on these two numbers is only fair, but we have assurance that the quality will be greatly improved. Pergamon Press has promised delivery of the other ten numbers of 1957 by late summer of 1958. Plans are under way to continue this on a more prompt time schedule for 1958. The project for the translation of Russian geophysical abstracts has been dropped.

General Secretary Sayre urged members to watch the minutes of the Executive Committee and Special Announcements in the *Transactions* for detailed word on these and other developments.

Report of the President

Vice President Berkner reported on two things on behalf of President Maurice Ewing, who could not attend the annual meeting because he is recuperating from an operation. The Executive Committee has been doing some detailed planning in order to meet the challenge of the increased quantity of geophysical information that will come from the IGY and from organized activities in geophysics generally. The plan evolved will be referred to the membership for ballot upon the recommendation of the Executive Committee. After careful study by a committee appointed by the President, a report was made, discussed at length, and accepted by the Executive Committee that, commencing with January 1, 1959, there will be issued two journals in the place of one. The first journal, *Research in Geophysics*, will contain only scientific and technological papers and related material, and will be published monthly. It will have page content sufficient to maintain a good balance of all geophysical interests with plans for substantial enlargement as the flow of papers increases. If this proposal is accepted, we must have aid in securing papers from the areas of geophysics that have not heretofore been well represented in the *Transactions*.

The Executive Committee also proposes that the *Transactions* be continued to carry news notes, reviews, and business of the Union, and perhaps descriptive material in the fields of geophysics of broad interest to science teachers. A real effort is being made to increase the advertising. The ballot will come to you for your decision within the next two or three months since it is hoped that final action can be taken and the journals issued on the new basis as of January 1, 1959. The Executive Committee has had a careful study of this in progress for over a year.

A very important Report of the Committee on International Participation will be published in the *Transactions* in August 1958. This brings to a head the discussions that proceeded over many years concerning the relation of AGU to the National Academy of Sciences and to the International Union of Geodesy and Geophysics. The proposal of the Committee was accepted as a basis for discussion at the meeting of the Executive Committee on May 4, 1958. Your comments and opinions are solicited. A change is dictated by urgent necessity. The Executive Committee feels that it is imperative that AGU retain its relationship as the U. S. National Committee of the IUGG since it is felt that the IUGG is the very heart of our work in the use of the Earth as a laboratory.

Reports of Standing Committees

Meetings—Chairman Philip H. Abelson noted that there have been a few departures from our usual meeting plan this year. Previously the Union program mainly consisted of short papers, but obviously when a man has done an exceptional piece of work he deserves a little longer time. The program next year will see something more of the evolution, and since IGY data will be available in great quantity and there will be more analyses, there will be more emphasis on reports from the IGY program. The meeting will be held May 4–6, 1959.

The Pacific Northwest Regional Meeting will be held in Portland, Oregon, November 13–14, 1958.

On behalf of the Union, Vice President Berkner thanked the Committee on Cosmic-Terrestrial Relationships for the arrangment of their symposium before the Section of Geomagnetism and Aeronomy, and N. C. Gerson for arrangement of the Symposium on Satellite Geophysical Studies, and to the many who worked out programs for the Sections. He also noted that the Union owes Chairman Abelson a special vote of thanks for not only arranging the program, Frontiers in Geophysics, but also for all other arrangements for the meeting.

Reports of Special Committees

Resolutions—In the absence of Chairman John N. Atkins, Hatten S. Yoder presented the following resolution which was adopted by the Section of Geodesy:

RESOLVED, That the system of weights and measures in general use in the United States today has been rendered obsolete by nearly world-wide adoption of the metric system, and

That accelerating international communication of technological and scientific data imposes a growing burden of conversion from one system into the other, and

That, therefore, the Congress of the United States should be urged to enact a law abolishing the current system and making compulsory the metric system, this conversion to be initiated immediately by means of education, but not be finally effective for a period of one human generation, or approximately thirty years.

A motion was approved that this matter be referred to a Union committee for study and report.

The following resolutions were then presented which were unanimously adopted:

(1) RESOLUTION TO FURTHER GRAVITY MEASUREMENTS IN THE NORTH ATLANTIC FOR THE PURPOSE OF GEOID DETERMINATION

WHEREAS, The American Geophysical Union, recognizing the discrepancy between the geoid in Europe as given by astrogeodetic methods and that given by gravimetric methods, and recognizing further that these discrepancies might be reconciled by gravimetric studies in the northern portion of the North Atlantic, joins with the Study Group of the International Association of Geodesy charged with the determination of a geoid profile connecting the European and American networks in urging agencies having sea gravity meters to study the area of the North Atlantic, especially the Norwegian Sea, therefore be it

RESOLVED, That a copy of this resolution be sent to the Secretary of Defense.

(2) RESOLUTION OF THANKS FOR THE USE OF FACILITIES

WHEREAS, The success of the Pacific Northwest Regional Meeting at Pullman, Washington, October 29–30, 1957, was due in large part to the space and facilities generously provided by the State College of Washington, therefore be it

RESOLVED, That the thanks of the American Geophysical Union be extended to the State College of Washington for the use of their meeting rooms and other facilities, and that the General Secretary be instructed to forward a copy of this resolution to the appropriate official of the State College of Washington.

(3) RESOLUTION OF THANKS FOR THE USE OF FACILITIES

WHEREAS, The success of the Pacific Southwest Regional Meeting at Pasadena, California, February 6–7, 1958, was due in large part to the space and facilities generously provided by the California Institute of Technology, therefore be it

RESOLVED, That the thanks of the American Geophysical Union be extended to the California Institute of Technology for the use of their meeting rooms and other facilities, and that the General Secretary be instructed to forward a copy of this resolution to the appropriate official of the California Institute of Technology

(4) RESOLUTION OF THANKS FOR THE USE OF FACILITIES

WHEREAS, The District of Columbia Chapter of the American Red Cross has provided the use of its Auditorium for the Thirty-Ninth Annual Meeting of the American Geophysical Union, therefore be it

RESOLVED, That the American Geophysical Union express its great appreciation of this cooperation and instructs the General Secretary to express the thanks of the Union to the appropriate official.

(5) RESOLUTION OF THANKS FOR THE USE OF FACILITIES

WHEREAS, The National Academy of Sciences has provided the use of meeting rooms and other services for the Thirty-Ninth Annual Meeting of the American Geophysical Union, therefore be it

RESOLVED, That the American Geophysical Union express its great appreciation of this cooperation, extended over many years, and instructs the General Secretary to express the thanks of the Union to the appropriate official.

(6) RESOLUTION OF THANKS FOR THE USE OF FACILITIES

WHEREAS, The United States Public Buildings Administration has provided the use of a meeting room and other services for the Thirty-Ninth Annual Meeting of the American Geophysical Union, therefore be it

RESOLVED, That the American Geophysical Union express its great appreciation of this cooperation, extended over many years, and instructs the General Secretary to express the thanks of the Union to the appropriate official.

(7) RESOLUTION OF THANKS FOR THE USE OF FACILITIES

WHEREAS, The Department of the Interior has provided the use of its Auditorium for the Thirty-Ninth Annual Meeting of the American Geophysical Union, therefore be it

RESOLVED, That the American Geophysical Union express its great appreciation of this cooperation and instructs the General Secretary to express the thanks of the Union to the appropriate official.

An informal resolution was also adopted extending the Union's best wishes for good health and speedy recovery to President Ewing.

Adjournment—The meeting adjourned at 16h 44m.

A. NELSON SAYRE, General Secretary
WALDO E. SMITH, Executive Secretary

Appendix A—Minutes of the Annual Meeting of 1958, Section of Geodesy, American Geophysical Union

President Schmidt called the meeting to order in the Auditorium of the D. C. Chapter, American Red Cross, at 09h 15m on May 5, 1958. There was no business to transact except adoption of resolutions which was deferred until the scientific session was completed.

The scientific session proceeded with the reading of the following papers:

(1) FLOYD W. HOUGH: The Role of the Geodesist
(2) C. A. WHITTEN: Distortion in Continental Triangulation
(3) R. K. C. JOHNS: Adjustment of Conditioned Observations with Unknowns
(4) HAL P. DEMUTH: Applications of the Tellurometer
(5) CARL I. ASLAKSON: Geodetic Control in Jungle Areas
(6) IRENE FISCHER: A Tentative World Datum from Geoidal Heights

The session recessed at 11h 35m and reassembled at 14h 00m and proceeded with the following papers:

(7) W. A. HEISKANEN[a] AND U. A. UOTILA: An Accuracy of the Gravimetric N, ξ, and η
(8) W. M. KAULA: A Statistical and Harmonic Analysis of Gravity
(9) J. LAMAR WORZEL: Gravity Measurements on a Surface Ship with the Graf Sea Gravimeter
(10) JOHN A. O'KEEFE: Report of AGU Committee on Geodetic Applications of Artificial Satellites
(11) FREDERICK S. DOYLE: Place for Geodesy in the University Curriculum
(12) J. C. ROSE[a], G. P. WOOLLARD, AND R. M. IVERSON: Gravity Standardization Measurements with the Gulf Pendulums in Australia and New Zealand

[a] Denotes speaker.

Business Session—Two resolutions were submitted and adopted without dissent by the Section to be submitted to the Union (see Union minutes, above) as follows:

(1) A resolution submitted by Finn E. Bronner for adopting the metric system in the United States by means of education and legislation to be finally effective after a period of one human generation, or approximately thirty years.

(2) A resolution submitted by John A. O'Keefe urging agencies with sea gravity meters to study the area of the North Atlantic, especially the Norwegian Sea, in order to reconcile the difference in the determination of the geoid in Europe by astrogeodetic means with the determination by gravimetric methods.

The meeting adjourned at 16h 45m.

FRANK L. CULLEY, Secretary

Appendix B—Minutes of the Annual Meeting of 1958, Section of Seismology, American Geophysical Union

President Benioff opened the Thirty-Ninth Annual Meeting of the Section of Seismology with a brief Business Session at 09h 00m, May 5, 1958, in the Reading Room of the National Academy of Sciences. The minutes of the Thirty-Eighth Annual Meeting of the Section were approved as published [*Trans.*, **38**, 440, 1957]. President Benioff announced the appointment of a committee to arrange for the next meeting to be held jointly, if feasible and mutually agreeable, with the Eastern Section of the Seismological Society of America (L. M. Murphy and Benjamin F. Howell, Jr.). There being no other business, the Business Session was terminated, and the following papers were presented at the Scientific Sessions.

(1) T. GOLD AND D. H. MENZEL: A New Method for Obtaining Seismic Information
(2) R. P. MEYER, J. S. STEINHART, AND G. P. WOOLLARD: Seismic Determination of the Crustal Structure in the Central Plateau of Mexico
(3) DAVID E. WILLIS, ROBERT C. FITZPATRICK, AND J. T. WILSON: Some Observations on the Rainier Underground Nuclear Detonation
(4) LESLIE F. BAILEY AND CARL ROMNEY: Seismic Waves from the Nevada Underground Explosion of September 19, 1957
(5) CARL KISSLINGER: Observations of the De-

velopment of the Surface Wave Pattern in the Vicinity of Small Explosions

(6) A. E. Scheidegger: Tectonophysical Significance of Fault Plane Solutions of Earthquakes in the Northwest Pacific

(7) W. S. Jardetzky: On a Direct Representation of a Disturbance in an Elastic Medium

(8) J. H. Rosenbaum: A Note on the Propagation of a Sound Pulse in a Two-Layer Liquid Medium

After a noon recess, the following papers were presented.

(9) L. Knopoff, J. F. Gilbert, and W. L. Pilant: Pulse Propagation in a Medium with a Single Layer

(10) Howard E. Tatel*, Merle A. Tuve, and Colleagues: Carnegie Seismic Expedition to the Andes, 1957

(11) Frank Press: Velocity Distribution in the Crust

(12) M. Landisman and Y. Sato: Shear Wave Velocities in the Upper Mantle

(13) Jack Oliver and Maurice Ewing: Short-Period Oceanic Surface Waves of the Rayleigh and First Shear Modes

(14) Hugo Benioff and Frank Press: Progress Report on Long-Period Seismograph Recording

(15) N. Blaik, J. Northrop, and C. S. Clay: Some Seismic Profiles Onshore and Offshore Long Island, New York

(16) Walter C. Beckmann, Archie C. Roberts, and Bernard Luskin: Sub-bottom Depth Recorder Survey of Western Long Island Sound

(17) Cecil A. Nanney: A Study of Correlations between Earthquakes and Microseisms

* Deceased November 15, 1957.

James A. Peoples, Jr., Secretary

Appendix C—Minutes of the Annual Meeting of 1958, Section of Meteorology, American Geophysical Union

The Thirty-Ninth Annual Business Meeting of the Section of Meteorology was called to order by President Landsberg at 09h 00m, May 5, 1958, in the Great Hall of the National Academy of Sciences.

As the first item of business, the President obtained approval of the minutes of the Thirty-Eighth Annual Meeting as published [*Trans.*, **38**, 441–443, 1957].

A Resolutions Committee consisting of Chan N. Tuart was appointed, and the announcement of the Nominating Committee appointments was made. The latter consists of Sigmund Fritz, Chairman; Charles L. Hosler, and John C. Freeman.

Conrad Mook, Meteorological Editor for the *Transactions*, then gave a resumé of his editorial activities during the year.

There being no further business, the President adjourned the Business Session at 09h 15m.

The scientific sessions, held jointly with the American Meteorological Society, consisted of the papers listed in the following program.

Monday, May 5, 1958, 09h 00m, Great Hall,
National Academy of Sciences

Meteorology of the High Atmosphere (Richard A. Craig, Chairman)

(1) Paul Julian, William R. Larue, and Hans Panofsky: Estimation of 100-mb Flow from 500-mb Space Smoothed Charts (15 min.)

(2) J. K. Angell: An Analysis of Routine 300-mb Transosonde Flights from Japan (15 min.)

(3) Donald R. Purdy: Some Examples of the Variability of Winds at 300-mb (10 min.)

(4) W. Lawrence Gates: On the Estimation of Vertical Motion at the Tropopause (15 min.)

(5) Edward S. Epstein: The Three-dimensional Field of Motion in the Lower Stratosphere (15 min.)

(6) Sidney Teweles: A Study of Anomalous Warming of the Stratosphere (15 min.)

Monday, May 5, 1958, 14h 00m, Great Hall,
National Academy of Sciences

Symposium—Observational Limitations on the Accuracy of Analysis and Forecasting (Philip D. Thompson, Chairman)

(7) N. E. Laseur: Observational Limitations on the Accuracy of Analysis in Low Latitudes (30 min.)

(8) Charles L. Bristor: The Effect of Data Coverage on Forecast Accuracy (20 min.)

(9) Morton G. Wurtele: A Statistical Assessment of Predictability by Numerical Forecasting (30 min.)

(10) K. R. Johannessen: Some Studies of 'Weather' as an Initial Value Problem (20 min.)

(11) Thomas A. Gleeson: Probability of Observing Specific Phenomena from Network Stations (20 min.)

Tuesday, May 6, 1958, 09h 00m, Lecture Room,
National Academy of Sciences

Statistical Meteorology and Forecasting (Thomas F. Malone, Chairman)

(12) Glenn W. Brier and Isadore Enger: Weather Probabilities Several Months in Advance and Possible Operational Use (15 min.)

(13) R. A. Allen: A Note on Long-Range Prediction (15 min.)

(14) Edward N. Lorenz: Non-Linear versus Linear Objective Weather Predictions (15 min.)

(15) Iver A. Lund, Eugene J. Aubert, and Albert Thomasell, Jr.: Some Six-hour Predictions prepared by Statistical Methods (15 min.)

(16) William C. Spreen and Irving Solomon: An Indirect Method for Estimating the Frequencies of Ceilings Below Various Altitudes and within Various Altitude Ranges (15 min.)

(17) **Irving I. Gringorton**: Equivalent Tail-Wind Errors of Forecast and In-Flight Observation (15 min.)

(18) **Adam Kochanski**: Route Winds for Flights at 300 and 200 mb (15 min.)

Tuesday, May 6, 1958, 09h 00m, Auditorium,
Department of the Interior

Meso- and Micro-Scale Meteorology (Robert D. Fletcher, Chairman)

(19) **Tetsuya Fujita**: Precipitation and Cold-Air Production in Thunderstorm Highs (15 min.)

(20) **Chester W. Newton and Harriet R. Newton**: Interactions between Large Convective Rainstorms and Environmental Wind Field (15 min.)

(21) **W. Smith, I. Kaplan, and B. Herman**: The Life Cycle of the Meso-Systems Associated with the May 7–8, 1956 Severe Storms in Texas (15 min.)

(22) **Morris Tepper**: The Formation of Atmospheric Gravity Waves on an Inversion Surface by the Transit of an Upper-Air Isotach Maximum (15 min.)

(23) **William P. Elliott**: The Area within a Concentration Isopleth for Diffusion of SO_2 from a Continuous Point Source (15 min.)

(24) **R. R. Braham, Jr., E. L. Harrington, and T. E. Hoffer**: Use of Refractive Index Turbulence for Estimating Mechanical Turbulence in the Atmosphere (15 min.)

Tuesday, May 6, 1958, 14h 00m, Auditorium,
Department of the Interior

Meso- and Micro-Scale Meteorology (Morris Tepper, Chairman)

(25) **Tetsuya Fujita**: Analysis of the Fargo Tornado of June 20, 1957 (15 min.)

(26) **Walter H. Hoecker, Jr.**: Comparison of Dimensional and Time-Trend Characteristics of Some Tornadoes and Waterspouts (15 min.)

(27) **Ralph J. Donaldson, Jr.**: Radar Echo Characteristics of Hailstorms and Other Severe Thunderstorms (15 min.)

(28) **Homer W. Hiser**: Anomalous Radar Propagation in South Florida (15 min.)

(29) **David Atlas**: New Evidence of Meteorological 'Angel' Echoes (15 min.)

(30) **A. K. Blackadar**: Frictionally Induced Momentum Oscillations and Motion Patterns in the United States (10 min.)

(31) **L. F. Conover**: Sub-Tropical Clouds as Shown by Time-Lapse Photography (10 min.)

Wednesday, May 7, 1958, 09h 00m, Auditorium,
D.C. Chapter, American Red Cross

General Session (George Cressman, Chairman)

(32) **Jerome Namias**: Improvements in Extended Forecasting Resulting from Employment of Numerical Methods (15 min.)

(33) **Hans A. Panofsky and V. R. K. Rao**: The Relation between Lagrangian and Eulerian Correlation (15 min.)

(34) **L. Machta**: On the Use of Carbon-14 as a Tool in Meteorology (15 min.)

(35) **R. R. Braham, Jr.**: Cloud Duration as an Important Parameter in Cloud Seeding (15 min.)

(36) **Floyd C. Elder and Donald J. Portman**: Some Measurements of the Atmospheric Radiation at Colorado Springs and at the Summit of Pikes Peak (15 min.)

(37) **Robert G. Fleagle**: Comments on Turbulent Transfer at the Sea Surface (15 min.)

Thursday, May 8, 1958, 09h 00m, Lecture Room,
National Academy of Sciences

Physical Meteorology (Ferguson Hall, Chairman)

(38) **Charles L. Hosler**: The Role of Dilute Solutions in Nucleating the Ice Phase (15 min.)

(39) **Gilbert D. Kinzer and W. E. Cobb**: Analysis of the Growth and Collection Efficiency of Cloud Droplets (15 min.)

(40) **W. E. Cobb and Gilbert D. Kinzer**: Laboratory Measurements of the Growth of Cloud Droplets (15 min.)

(41) **Paul A. Allee and B. B. Phillips**: Measured Values of Droplet Charge, Polar Conductivities, and Potential Gradients in Supercooled Orographic Cumuliform Clouds (15 min.)

(42) **B. B. Philips and Gilbert D. Kinzer**: Measurements of the Size and Electrification of Droplets in Cumuliform Clouds (15 min.)

(43) **Bernice Ackerman**: Liquid Water Contents of Tropical Cumuli (15 min.)

(44) **Christian E. Junge**: The Sulfur Budget in the Atmosphere (15 min.)

Thursday, May 8, 1958, 09h 00m, Great Hall,
National Academy of Sciences

Symposium—Tropical Cyclones (Gordon Dunn, Chairman)

(45) **C. L. Jordan**: The Thermal Structure of the Hurricane Core (20 min.)

(46) **N. E. Laseur**: Detailed Low-Level Wind and Pressure Data from Hurricane Edith, 1955 (20 min.)

(47) **R. H. Simpson**: Horizontal Eddies in the Hurricane Circulation (20 min.)

(48) **Harry F. Hawkins**: Hurricane Winds at Flight Levels Related to Low-Level Wind Data (15 min.)

(49) **Robert C. Gentry**: Use of Winds Inside the Strong Vortical Circulation of Hurricanes to Predict Storm Movement (15 min.)

(50) **L. F. Hubert**: Distribution of Surface Friction in Hurricanes (15 min.)

Thursday, May 8, 1958, 14h 00m, Great Hall,
National Academy of Sciences

Tropical Meteorology (Werner A. Baum, Chairman)

(51) **William H. Haggard**: The Birthplace of North Atlantic Tropical Storms (15 min.)

(52) **Emanuel M. Ballenzweig**: Formation of Tropical Storms Related to Anomalies of the Long-Period Mean Circulation (15 min.)

(53) **Robert M. Cunningham**: Details of At-

mospheric Structure in and Around Bahaman Cumulus (15 min.)

(54) **Akira Kasahara**: A Comparison between Geostrophic and Quasi-Nongeostrophic Numerical Forecasts of Hurricane Movement with the Steering Model (15 min.)

(55) **Donald L. Jorgensen**: Predicting Atlantic Coast Hurricanes by Means of Synoptic-Climatological Relationships using Orthogonal Polynomials (15 min.)

(56) **Louis Berkofsky**: Some Preliminary Results of Numerical Hurricane Formation Prediction (15 min.)

Thursday, May 8, 1958, 14h 00m, Lecture Room, National Academy of Sciences

Climatology (Woodrow C. Jacobs, Chairman)

(57) **Isadore Enger**: The Period of Time Required to Determine a Daily Normal (15 min.)

(58) **H. C. S. Thom**: The Distribution of Annual Tropical Storm Frequency (15 min.)

(59) **J. Murray Mitchell, Jr.**: A New Test for Homogeneity of Historical Temperature Records (15 min.)

(60) **Oskar Essenwanger**: Frequency Distribution of Precipitation in a Logarithmic Scale (15 min.)

(61) **Oscar E. Richard**: Comparison of Methods of Computing Degree Days (15 min.)

(62) **J. Murray Mitchell, Jr.**: Effect of Changing Observation Time on Mean Temperature (10 min.)

(63) **John T. McCabe and Thomas D. Potter**: A Method for the Construction of Climatological Fallout Patterns (10 min.) Read by **Lester Machta**.

Woodrow C. Jacobs, Secretary

Appendix D—Minutes of the Annual Meeting of 1958, Section of Geomagnetism and Aeronomy, American Geophysical Union

The Thirty-Ninth Annual Meeting of the Section of Geomagnetism and Aeronomy was called to order at 09h 00m, May 6, 1958, in the Great Hall, National Academy of Sciences, by President Henry R. Joesting. There were approximately 110 members and guests in attendance. The minutes of the 1957 meeting were approved as published [*Trans.*, **38**, 443–444, 1957]. There being no old or new business, the first scientific session was started at once. This session was devoted to a Symposium on Cosmic-Terrestrial Relationships, Walter Orr Roberts acting as Chairman. The following papers were presented:

(1) **Sydney Chapman**: The Terrestrial Implications of Thermal Conduction in the Solar Corona; invited comments: Eugene N. Parker

(2) **Joseph W. Chamberlain**: The Present State of Speculation about the Origin and Acceleration of Aurora-Producing Particles; invited comments: S. F. Singer, Constance Warwick, and R. Jastrow

(3) **John A. Simpson**: What We Have Learned about Planetary Magnetic Fields and the Production of Cosmic Rays from the Flare of February 23, 1956; invited comments: John R. Winckler, Scott E. Forbush, and Dana K. Bailey

The second scientific session was called to order by President Joesting at 09h 00m on May 7 in the Great Hall, National Academy of Sciences, with about 90 members and guests in attendance. The following papers were presented:

(4) **J. D. Stolarik**[a], **I. R. Shapiro, and J. P. Heppner**: The F-ΔD-ΔI Ground Station Magnetometers for Project Vanguard

(5) **C. M. Carmichael**[a], **and R. J. Uffen**: Remanent Magnetization of Some Allard Lake Ilmenites

(6) **R. R. Doell**: Paleomagnetic Interpretations

(7) **S. F. Singer**: Role of Ringcurrent in Magnetic Storms

(8) **Leo R. Davis**[a] **and Otto E. Berg**: Rocket Measurements of the Electron and Ion Fluxes in an Aurora

(9) **E. P. Bialecke**[a] **and A. A. Dougal**: Laboratory Measurements of the Recombination Coefficient of Electrons and Ions in Nitrogen Gas at Very Low Electron Temperatures

(10) **Alfred J. Zmuda**: A Method of Analyzing Values of the Scalar Magnetic Intensity

(11) **John F. McClay and Paul F. Fougere**[a]: Mutually Consistent Spherical Harmonic Analysis

(12) **Kurt Toman**: A Statistical Relationship between Sunspots and M-Regions

(13) **Edwin J. Chernosky**: Geomagnetic H Intensity before and after a Disturbed (5 D) Day

During both of the scientific sessions there was active informal discussion from the floor following the presentation of each paper. The meeting was adjourned at 11h 50m.

R. E. Gebhardt, Secretary

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[a] Denotes speaker.

Appendix E—Minutes of the Annual Meeting of 1958, Section of Oceanography, American Geophysical Union

President Roger Revelle called the meeting to order at 09h 15m, May 6, 1958, in the Reading Room, National Academy of Sciences. There were approximately 40 members of the Section in attendance.

Since no corrections had been received, or were made from the floor, the minutes of the 1957 meeting were approved as published [*Trans.*, **38**, 444, 1957].

President Revelle announced the appointment of the Nominating Committee, composed of D. E. Carritt, *Chairman*; R. S. Arthur; B. C. Heezen; R. C. Vetter; and W. S. Von Arx.

An announcement was made by President Revelle concerning the proposed International Oceanographic

Congress to be held in early September, 1959, at the United Nations Building, New York.

John Lyman reported to the Section the decisions reached by the Executive Committee of the Union regarding publications, composition of the Executive Committee, and dues.

The Secretary presented a brief statement to the members of the Section regarding the problems associated with the planning of the program for the scientific sessions. Nearly two-thirds of the papers were received after the official closing date for the program.

The Business Meeting was then adjourned and the scientific sessions commenced. Because of the number of late papers, the program as presented and printed herewith differed considerably from that printed in the program.

(1) J. E. CHAPPELEAR: The Calculation of Wave Forces on Groups of Vertical Cylinders
(2) L. E. BORGMAN: An Algorithm for the Ocean Wave Forces on Inclined Cylinders
(3) A. H. SCHOOLEY: Profiles of Wind-Created Water-Waves in the Capillary-Gravity Transition Region
(4) W. J. PIERSON: Linear and Non-Linear Problems in Wave Theory for Waves Influenced by Both Gravity and Surface Tension
(5) R. O. REID: Effect of Coriolis Force on Edge Waves; Part I
(6) K. KAJIURA: Effect of Coriolis Force on Edge Waves, Part II (presented by R. O. Reid)
(7) D. L. ANDERSON[a] AND W. F. WEEKS: A Theoretical Analysis of Sea-Ice Strength
(8) T. S. AUSTIN: Variations with Depth of Oceanographic Properties along the Equator (presented by E. D. Stroup)

Tuesday, May 6, 1958, 14h 00m, Lecture Room, National Academy of Sciences

(9) W. B. BAILEY: On the Dominant Flow in the Strait of Belle Isle
(10) W. H. MUNK AND RICHARD HAUBRICH: The Polar Tide
(11) H. B. STEWART: Net Upstream Flow of Bottom Water in New York Harbor
(12) J. B. SMITH, LELA M. JEFFREY, AND D. W. HOOD[a]: Evidence for the Presence of Carbamino Carboxylic Acids in Sea Water
(13) J. H. CARPENTER: The Solubility of Oxygen in Water
(14) B. J. GILETTI: Circulation Rates of Near-Surface Atlantic Ocean Waters and the Cosmic-Ray Production of Tritium
(15) W. S. BROECKER, K. K. TUREKIAN[a], AND B. C. HEEZEN: The Relation of Deep-Sea Sedimentation Rates to Variations in Climate
(16) I. I. SCHELL: A Reconciliation of an Increased Circulation Characteristic of an Ice Age with a Decrease in Temperature and Solar Radiation

Wednesday, May 7, 1958, 09m 00m, Lecture Room, National Academy of Sciences

(17) J. R. LUMBY: Present Status of the Data Center (A) for Oceanography
(18) W. T. MCGUINNESS AND W. L. DONN[a]: The IGY-Island Observatories: Atlantic
(19) W. L. DONN[a] and W. T. MCGUINNESS: Seiches in Grindavik Harbor, Iceland
(20) L. E. EBER[a] AND O. E. SETTE: Indices of Variations in Strength of Atmospheric Circulation over the Pacific Ocean
(21) B. D. ZETLER[a], H. B. STEWART, AND C. B. TAYLOR: Recent Ocean Temperature and Sea Level Anomalies on the West Coast
(22) M. P. WENNEKENS: Hydrography of the Straits of Florida
(23) D. F. LEIPPER: The Impact on Oceanography of the NAS Meteorology Report
(24) D. F. LEIPPER: Staff and New Facilities in Oceanography at Texas A & M

As a result of questions raised by D. L. Leipper's presentation of the next to last paper, the Executive Secretary of the newly formed Committee on Oceanography of the National Academy of Sciences, R. C. Vetter, outlined some of the activities of the Committee for the assembled members.

DONALD W. PRITCHARD, Secretary

[a] Denotes speaker.

Appendix F—Minutes of the Annual Meeting of 1958, Section of Volcanology, Geochemistry, and Petrology, American Geophysical Union

President Schairer called the meeting to order at 14h 00m, May 5, 1958. No corrections to the minutes of the Annual Meeting of 1957 were received. President Schairer discussed briefly the concern of our Section for broadening the scope of activities of the International Association of Volcanology, the activities of the Eleventh General Assembly of the IUGG, and the plans for the Twelfth General Assembly in Helsinki in 1960. The Nominating Committee, appointed by the President to provide a slate of Section officers to take office after the meeting in 1959, includes W. W. Rubey, Chairman; O. F. Tuttle; and G. R. Tilton. The technical sessions began at 09h 00m, May 5. The program sponsored by our Section was as follows:

Monday, May 5, 1958, 09h 00m, Auditorium, General Services Building

(1) A. W. LAWSON AND JOHN C. JAMIESON[a]: Energy Transfer in the Earth's Mantle
(2) KENNETH O. BENNINGTON: Energy Transfer during Metamorphic Differentiation
(3) ANATOL J. SHNEIDEROV: On the Internal Temperature of the Earth
(4) LEON KNOPOFF AND GORDON J. F. MACDONALD: The Magnetic Field and the Central Core of the Earth
(5) GORDON J. F. MACDONALD AND LEON KNOPOFF: The Chemical Composition of the Outer Core

(6) Robert J. Uffen: On the Origin of Rock Magma

(7) F. W. Dickson: Zone Melting as a Mechanism of Intrusion: A Possible Solution of the Room and Superheat Problems

(8) P. J. Wyllie and O. F. Tuttle: Hydrothermal Experiments on the Melting Temperatures of Shales

(9) P. J. Wyllie: The Fusion of Torridonian Sediments by a Picrite Sill in Soay (The Hebrides)

(10) A. E. Beck and J. M. Beck: On the Measurement of the Thermal Conductivity of Rocks by Observations on a Divided Bar Apparatus

Monday, May 5, 1958, 14h 00m, Auditorium, General Services Building

(11) Adrian F. Richards and James M. Snodgrass: Volcano Acoustics

(12) Robert L. Smith, Irving Friedman, and William D. Long: Welded Tuffs, Experimental I

(13) Irving Friedman and Robert L. Smith: The Hydration of Obsidian Artifacts

(14) Philip M. Orville: Composition of Unzoned Pegmatites in Southern Black Hills, South Dakota

(15) E. H. Roseboom, Jr.[a] and G. Kullerud: The Solidus in the System Cu-Fe-S between 400° and 800°C

(16) Lloyd A. Clark: Phase Relations in the System Fe-As-S

(17) H. J. Van Hook: A Preliminary Report on the System Ag_2S-Bi_2S_3-PbS

(18) W. S. Broecker and A. Walton: C^{14}/C^{12} Ratios in Fresh Water Systems

(19) W. Compston[a] and S. Epstein: A Method for the Preparation of Carbon Dioxide from Water Vapour for Oxygen Isotope Analysis

Tuesday, May 6, 1958, 09h 00m, Auditorium, General Services Building (E. P. Henderson, Chairman)

(20) Paul B. Barton, Jr., and Philip M. Bethke: Approximate Single Ion Activity Coefficients from pH Measurements

(21) Donald W. Groff: A Graphic Approach to Meaningful Radiometry

(22) John W. Winchester: Sodium and Potassium Determination by Neutron Activation

(23) Walter Nichiporuk and Arthur Chodos: Concentration of Vanadium, Chromium, Cobalt, Nickel, and Zinc in the Troilite Phase of Meteorites

(24) E. L. Fireman: A^{39} in the Sikhote-Alin Meteorite and Its A^{39}-A^{38} Age

(25) John H. Hoffman and Alfred O. Nier: Cosmogenic Helium Distribution in Iron Meteorites

(26) O. A. Schaeffer and J. Zähringer: The Rare Gas Contents of Iron Meteorites

(27) Royal R. Marshall and David C. Hess: Lead from Stone Meteorites

(28) Paul W. Gast: Isotopic Abundance of Sr^{87} in the Earth and Meteorites

Tuesday, May 6, 1958, 14h 00m, Auditorium, General Services Building (P. M. Hurley, Chairman)

(29) R. K. Wanless and G. B. Leech: Lead Isotope Studies of the Sullivan and Other Deposits in the East Kootenay District, Southeastern British Columbia

(30) R. D. Russell, R. M. Farquhar, and R. L. Stanton: A Revised Interpretation of the Isotope Ratios of Common Lead

(31) E. J. Catanzaro and P. W. Gast: Isotopic Composition of Lead in Pegmatitic Feldspars

(32) A. Walton and W. S. Broecker: Recent Results on the Ionium Method of Age Determination

(33) Donald S. Miller and J. Laurence Kulp: New Isotope Data and the Colorado Plateau Uranium Mineralizations

(34) G. R. Tilton, G. L. Davis, and G. W. Wetherill: The Age of the Baltimore Gneiss

(35) J. Laurence Kulp and L. E. Long: Chronology of Major Metamorphic Events in Southeastern United States

(36) S. S. Goldich, A. O. Nier, H. W. Krueger[a], and J. H. Hoffman: K-A Dating of Precambrian Iron Formations

(37) S. S. Goldich[a], A. O. Nier, and H. Baadsgaard: Three-fold Division of Precambrian in the Lake Superior Region

This program is one-third greater than that of last year and in spite of the experience of this year's officers the schedule was too strenuous to permit the amount of discussion desired. The larger program again allowed the formation of somewhat more homogeneous sessions which reduce the shuffle between papers to a minimum.

L. Thomas Aldrich, Secretary

[a] Denotes speaker.

Appendix G—Minutes of the Annual Meeting of 1958, Section of Hydrology, American Geophysical Union

Vice-President Harry F. Blaney called the Business Meeting to order at 09h 15m, May 5, 1958, in the Lecture Room, National Academy of Sciences. The Vice-President conveyed President Ray K. Linsley's regrets that he was not able to participate in the meeting. President Linsley currently is in London, England, under a Fulbright Fellowship.

Chairman Blaney introduced J. Th. Thijsse of the Technical University of Delft, The Netherlands, Past-President of International Association of Hydrology and the 1958 recipient of the AGU William Bowie Medal. The Chairman stated that the Section was honored and pleased to have Professor Thijsse attend our meetings. W. G. Hoyt, one of the founder members of the Section of Hydrology, was also introduced.

Secretary Wilson reported on recommendations of the Hydrology Nominating Committee for Section officers for the next triennium. The Nominating Committee consists of H. G. Wilm, Chairman; F. J. Veihmeyer; and Arthur Johnson. The Hydrology Executive Committee approved the following nominations and will request the Nominating Committee to select another candidate for Vice-President to replace the previously selected second candidate who found it necessary to withdraw his name:

For President: Harry F. Blaney
Walter B. Langbein
For Vice-President: William E. Hiatt
(to be named)
For Secretary: Charles C. McDonald
Ralph N. Wilson

The Secretary announced that, upon recommendation of the Hydrology Committee on Awards, the Executive Committee selected the paper, Moisture Movement in Porous Materials under Temperature Gradients by J. R. Philip and D. A. deVries as the best Hydrology paper to appear in the *Transactions* of 1957 and that this paper is to receive the Horton Award for that year. A Certificate of Award will be prepared and forwarded to each author at an early date.

Secretary Wilson reported that C. C. Warnick, Chairman, Hydrology Research Committee on Snow, Ice, and Glaciers, is handling arrangements regarding U.S. participation in the Symposium on Physics of Ice Movement, sponsored by the International Association of Hydrology, IUGG. This Symposium will be held in Chamonix-Mont Blanc, France, September 16–24, 1958. Based on information received by Warnick to date, it appears that approximately ten U.S. papers will be submitted to IAH for the Symposium.

The Secretary announced that IAH is sponsoring a Symposium on Forests and Waters, to be held in Germany in August 1959. It is expected that upon establishment of questions to be considered, the various Hydrology Research Chairmen will invite U.S. individuals to prepare papers on the particular questions. Favorable response to these subsequent requests for papers will be appreciated.

The Business Meeting then adjourned and was followed immediately by the Scientific Sessions which consisted of two sessions on a Symposium on Vegetation and Land-Use Influences and two general sessions. The opening session of the Symposium, under the Chairmanship of Vice-President Blaney, began at 09h 35m and recessed at 12h 10m, with about 110 in attendance. The following scientific program was presented:

(1) H. P. Guy: A Method for Determining Trend of Suspended-Sediment Discharge in Streams
(2) Howard Busch[a] and G. Robert Hall: Land Use Trends of the Brandywine Watershed
(3) Walter Langbein: Basic Hydrologic Data for Upstream Engineering and Land Management
(4) Nedavia Bethlahmy: Logging and Surface Runoff (presented by Bernard Frank)
(5) A. L. Sharp[a], A. E. Gibbs, and W. J. Owen: Problems Involved in Determining the Effects of Land Use and Treatment on Water Yields
(6) H. W. Anderson and R. L. Hobba[a]: Forests and Floods in the Northwest

The second session of the Symposium, under the Chairmanship of Howard L. Cook, began May 5 at 14h 00m in the Lecture Room, National Academy of Sciences. The following program was presented with about 80 members and guests present:

(7) Bernard Zeliner[a] and Carl D. Eklund: Hydrologic Effects of Land Use and Vegetation in the Chestuee and Beech River Watersheds in Tennessee
(8) H. F. Smith: The Effect of Urbanization on Runoff
(9) Marvin D. Hoover: Vegetation and Land-use Effects
(10) L. L. Kelly: Discussion of paper by Hoover
(11) Harry F. Blaney: Consumptive Water Requirements of Vegetative Cover in River Basins
(12) H. V. Peterson: Erosion and Sediment Problems on Western Arid Lands

The first general session was called to order by William C. Ackermann, May 6 at 14h 00m in the Reading Room, National Academy of Sciences. The Chairman acknowledged the presence in the audience of H. G. Wilm, President of the International Association of Hydrology. The session was well attended by approximately 100 members and guests.

(13) A. E. Scheidegger: The Random-Walk Model of Flow through Porous Media
(14) Irvin C. Reigner: Prediction of Streamflow for Single-Watershed Calibration
(15) G. N. Alexander: Return Period Relationships
(16) Harry E. Schwarz: Simulation of a Reservoir System
(17) M. Martinelli, Jr.: Some Hydrologic Features of Alpine Snowfields under Summer Conditions
(18) Donald J. Portman: Conductivity and Length Relationships in Heat-Flow Transducer Performance
(19) H. C. Riggs: Regional Frequency of Low Flows of Streams

The last general meeting was called to order by Walter B. Langbein. This session was opened at 09h 10m, May 7, in the Auditorium, General Services Building, and was attended by about 115 members and guests.

(20) Melvin H. Kleen[a] and William H. Sammons: Agricultural Watershed Influences on Runoff Potential
(21) C. E. Jacob: Salt-Water Encroachment in Inclined Confined Aquifers of Non-Uniform Thickness
(22) H. H. Cooper, Jr.: An Hypothesis Concerning the Dynamic Balance of Fresh Water and Salt Water in a Coastal Aquifer
(23) F. A. Huff[a] and J. C. Neill: Application of Several Statistical Methods to Rainfall Frequency Analysis
(24) D. L. Brakensiek[a] and R. K. Frevert: Estimation of Storm Surface Runoff by Infiltration Theory
(25) Dewey R. Soltow and Richard D. Tarble[a]: The Use of a Radar Beacon in Reporting Precipitation

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[a] Denotes speaker.

(26) G. E. Harbeck and G. E. Koberg[a]: A Method of Evaluating Effects of a Monomolecular Film in Suppressing Reservoir Evaporation

[a] Denotes speaker.

The meeting adjourned at 16h 45m with comments by the Secretary suggesting that authors promptly submit their papers to AGU for publication and expressing appreciation to the members for so actively supporting the Section meetings by their attendance and lively discussion of many of the papers.

Ralph N. Wilson, Secretary

Appendix H—Minutes of the Annual Meeting of 1958, Section of Tectonophysics, American Geophysical Union

The Business Meeting was called to order by President Hess at 09h 08m on May 7, 1958, in the Reading Room of the National Academy of Sciences. Appointment of a Nominating Committee to consist of Ernst Cloos (Chairman), M. King Hubbert, and L. L. Nettleton was announced. The question was raised whether the Nominating Committee should bring in one or two names for each office for the next election of officers. A large majority of members indicated that they felt one name for each office was appropriate. The technical session began at 09h 12m, and consisted of the following papers.

(1) Robert B. Dewey: Traction at Wave Velocity Discontinuities

(2) Hugh C. Heard: The Brittle to Ductile Transition in Solenhofen Limestone as a Function of Temperature, Confining Pressure, and Interstitial Fluid Pressure

(3) D. T. Griggs[a], F. J. Turner, H. C. Heard, and M. S. Paterson: Recrystallization in Calcite Crystals and Aggregates

(4) John Handin: Effects of Temperature on the Strengths of Some Sedimentary Rocks

(5) Aniruddha De: Observations on the Deformation Lamellae in Quartz of Four Indian Tectonites

(6) William F. Brace: Indentation and Plastic Properties of Certain Geologic Materials

(7) T. P. Thayer: Some Problems Related to Dating Peridotites and Intrusive Serpentinites

(8) Matthew F. Norton and Ross F. Giese, Jr.: The Role of Wrench Faulting in Orogeny

The technical session was completed at 11h 58m. President Hess again asked the members present to indicate whether they felt that one nominee per office was enough. On finding that a majority favored one nominee, he announced that as the By-Laws permitted this, a single slate will be presented at the next election. The meeting adjourned at 12h 00m.

B. F. Howell, Jr., Secretary

[a] Denotes speaker.

Union, Section, and Committee Activities

Pacific Southwest Regional Meeting Held in Pasadena, February 6–7, 1958—The annual meeting of the Pacific Southwest Region was held in Pasadena, February 6–7, 1958, with a total registration of 162, with perhaps about 200 in attendance. Six sessions were held, one a general session, another in oceanography and meteorology, another in meteorology and hydrology, one in oceanography, and two in hydrology. Some 25 papers were presented. A luncheon meeting was held at mid-day on February 6, at which the guest speaker was James F. Bonner, Professor of Biology at California Institute of Technology, who spoke on "World Population and World Food." Beyond the two days of meetings, field trips were held on Saturday, February 8, one from 8:00 until noon on the flood control and water conservation facilities of Los Angeles County, and the second from 8:00 until 3:00 as an excursion to the San Dimas Experimental Forest. In accordance with the By-Laws of the Region, the following are named members of the Committee on Nominations to nominate members for the triennium beginning July 1, 1959: Vito A. Vanoni, Eugene Bollay, Townsend Cromwell, and Robert E. Holzer, representing Hydrology, Meteorology, and Oceanography, which three Sections joined in the meeting in February. Townsend Cromwell has been added to the Committee for the current triennium to represent Oceanography, which was not hitherto represented on the Committee.

The meeting for 1959 is planned to be held at Stanford University, and an invitation is before the group to hold the Regional Meeting at the Scripps Institution of Oceanography in 1960.

Additions to the Membership

February 10, 1957 to April 10, 1958

Aarons, Dr. Jules, Air Force Cambridge Research Center, Bedford, Mass. (*d*) 57

Adler, Mr. Paul G., Graduate House (307A), Massachusetts Inst. of Technology, Cambridge 39, Mass. (*b*) 57 S.M.

Aguilar, Mr. Alonso, Jr., P. O. Box 2133, San Juan, Puerto Rico (*g*) 58

Alverson, Mr. James E., 2005 Hearst St., Berkeley 9, Calif. (*cg*) 56

Ambraseys Mr. Nicols N., Room 222, Dept of Soil Mechanics, Imperial College of Science, London, S.W. 7, England (*beg*) 57

Anderson, Mr. Daniel H., P. O. Box 5, Ashville, N. Y. (*df*) 58 S.M.

Andrews, Mr. Alday B., Oakwood Manor, Apt. 31-B, Evergreen and Hunter Streets, Woodbury, N. J. (*b*) 56 A.M.

Andrews, Mr. Gerald S., Surveys and Mapping Branch, Dept. of Lands and Forests, Victoria, B. C., Canada, (*adeg*) 57

Apell, Mr. Charles A., 558 Rutherford Ave., Trenton, N. J. (*abefgh*) 58

Axenfeld, Mr. Sheldon, Div. of Oceanography, U. S. Navy Hydrographic Office, Washington 25, D. C. (*de*) 58

Back, Mr. William, U. S. Geological Survey, Ground Water Branch, Washington 25, D.C. (*g*) 58

Bailey, Mr. Lothrop Hedge, P. O. Box 2038, Pittsburgh, Pa. (*ach*) 57

Baldrica, Mr. Donald J., U. S. Geological Survey, P. O. Box 3418, Portland, Ore. (*eg*) 57

Bali, Mr. Jaswant Singh, c/o Mr. V. P. Bakshi, 56/17 Rajendarnager, New Delhi, India (*g*) 57

Balle, Mr. Frank R., 27900 Hoover St., Center Line, Mich. (*g*) 57

Baltusnik, Mr. Joseph S., Phi Kappa Tau, State College, Pa. (*adh*) 57 S.M.

Barclay, Mr. Joseph E., 1547 Chowkeebinnene St., Tallahassee, Fla. (*g*) 57

Barela, Mr. Ralph Z., Arctic Research Laboratory, Box 1070, Fairbanks, Alaska, (*bd*) 58

Barraclough, Mr. Jack Thomas, P. O. Box 1233, Tallahassee, Fla. (*g*) 58

Bauer, Dr. Siegfried J., R. D. 2, Box 237B, Neptune, N. J. (*cd*) 57

Beck, Mr. Richard H., 901 Lincoln Ave., Stambaugh, Mich. (*abdf*) 57 S.M.

Behlke, Mr. Charles E., 419 N. 34 St., Corvallis, Ore. (*g*) 57

Bender, Mr. James A., 2129 Glenview Rd., Wilmette, Ill. (*g*) 57

Benert, Mr. Robert, Rt. 1, Box 199f, Libertyville, Ill. (*abg*) 57

Benfer, Mr. Neil A., 1815 Meadowbrook Rd., Charlottesville, Va. (*e*) 57

Bennett, Mr. John H., 1847 N. Verdugo Rd., Glendale 8, California (*ag*) 57

Bennett, Dr. Willard H., 174 Chesapeake St., S.W., Washington 24, D. C. (*d*) 57

Benson, Dr. Bruce B., Department of Physics, Amherst College, Amherst, Mass. (*e*) 57

Benson, Dr. William E., National Science Foundation, Washington 25, D. C. (*cefgh*) 57

Berg, Prof. Dr. Hellmut, Meteorologisches Institut der Universität, Koln, Germany (*bcdg*) 57

Berry, Mr. Roy Lee, 117-B Wonju Circle, Oceanside, Calif. (*bfgh*) 57

Best, Mr. Myron Gene, 1260 Hopkins, No. 47, Berkeley 2, Calif. (*bfh*) 57 S.M.

Betson, Mr. Roger P., Route 2, Louisville, Tenn. (*cg*) 57

Bhattacharya, Mr. Amiya P., Irrigation Research Institute, Roorkee, U. P., India (*cg*) 57

Bhimasankaram, Dr. V. L. S., Geophysikalisches Institut, Herzbergerland Strasse 180, Göttingen, Germany (*bdh*) 57

Bierly, Mr. Eugene W., 1835 Noartwood Apartments, Ann Arbor, Mich. (*c*) 57 S.M.

Bishop, Lt. Barry C., 6521 8th Pl., Hyattsville, Md. (*abcdefgh*) 57

Blake, Dr. F. Gilman, Jr., California Research Corp., P. O. Box 446, La Habra, Calif. (*bdh*) 57

Bowker, Mr. David E., 22 Blagden St., Boston 16, Mass. (*abde*) 57 S.M.

Braun, Mr. Lewis T., 3680 Newport St., Denver, Colo. (*fh*) 57

Brennan, Major Joseph X., Geophysics Research Directorate, L. G. Hanscom Field, Bedford, Mass. (*de*) 57

Brewer, Mr. Elijah, 2504 South Holly Avenue, Fresno, Calif. (*g*) 57

Brisbin, Prof. William C., Dept of Geology, University of Manitoba, Winnipeg, Man., Canada (*ah*) 57

Brittain, Capt. John H., 8501 Rayburn Road, Washintgon 14, D. C. (*ae*) 57

Brodbeck, Mr. Ernest E., 12 Terrace Court, Albertson, N. Y. (*g*) 57

Brooks, Mr. Billy Gene, 559 N. 5th St., Laramie, Wyo. (*b*) 57

Bronner, Mr. Finn Eyolf, 516 La Marina, Santa Barbara, Calif. (*abcdefgh*) 57

Brown, Mr. Alvin J., P. O. Box 380, Bakersfield, Calif (*bcg*) 57

Brown, Mr. Maurice W., 3218 Chenu Ave., Sacramento 21, Calif. (*cg*) 57

Brownlie, Mr. Wallace A., U. S. Geological Survey, P. O. Box 3418, Portland 8, Ore. (*g*) 57

Browzin, Mr. Boris S., Case Institute of Technology, University Circle, Cleveland 6, Ohio (*g*) 57

Bruington, Mr. Arthur E., 636 W. Hermosa Dr., San Gabriel, Calif., (*g*) 57

Bryan, Mr. Lester L., 4135 S. E. Oak St., Portland 15, Ore. (*g*) 57

Bryant, Mr. George T., 513 Ames Hall, Johns Hopkins University, Baltimore 18, Md. (*g*) 57

Butts, Mr. William Thomas, 727 California St., Tallahassee, Fla. (*bfh*) 58

Camp, Mr. Fred A., 1740 Lucile Ave., Los Angeles 26, Calif. (*g*) 57

Campbell, Mr. John M., General Motors Corp., Research Staff, P. O. Box 188, North End St., Detroit 2, Mich. (Corp. Mem. representative)

Canas-Abril, Prof. Petro E., Maso 457, Santiago, Cuba (*ce*) 57

Cantwell, Mr. Thomas, 34 Peacock Farm Rd., Lexington, Mass (*bdfh*) 57

Carlson, Mr. Hugh Douglas, Dept of Geology, University of South Dakota, Vermillion, S. Dak. (*f*) 58

Carter, Mr. Jack R., U. S. Geological Survey, Code 4042-5402, Washington 25, D. C. (*g*) 58

Case, Mr. James B., 994 River Road Dorm., Ohio State University, Columbus 10, Ohio (*a*) 58

Chapman, Mr. Robert M., 60 Hurd Rd., Belmont 78, Mass. (*c*) 57

Clark, Dr. Sydney P., Jr., Geophysical Lab., 2801 Upton St., N.W., Washington 8, D. C. (*dfh*) 57

Cohen, Mr. Bernard, 6052 Belden St., Philadelphia 49, Pa. (*g*) 57

Cohen, Mr. Charles, 5001 14th Ave., Brooklyn 19, N. Y. (*h*) 58 S.M.

Coles, Mr. Errol D., c/o Standard Bank of S. Afr., Cecil Square, Salisbury, Southern Rhodesia (*cg*) 57

Coltharp, Mr. George B., 933 K Cherry Lane, East Lansing, Mich. (*cg*) 58 S.M.

Constantinu, Mr. Constantin, Quinta Marianthi, Urbanizacion la Macarena, Parcela 3-B, Los Teques, Edo. Miranda, Venezuela (*ceg*) 58

Corchary, Mr. George S., U. S. Geological Survey, Washington 25, D. C. (*fg*) 57

Cornish, Mr. John H., 1569 N. Joplin Ave., Tulsa 15, Okla. (*cg*) 58

Corpaciu, Dr. Alexander, 4448 Faraday Place, N.E., Washington, D. C. (*abcde*) 57

Cox, Mr. Edward R., P. O. Box 425, Carlsbad, N. Mex. (*fg*) 58

Cresswell, Mr. George M., Jr., Woods Hole Oceanographic Inst., Woods Hole, Mass. (*e*) 58

Culbertson, Mr. James K., 2126 Leed S. E., Albuquerque, N. Mex. (*g*) 57

Currie, Dr. John Bickell, P. O. Drawer 2038, Pittsburgh 30, Pa. (*bfh*) 57

Davis, Mr. Willard E., 7504 Holly Ave., Takoma Park, Md. (*abdh*) 57

Dean, Mr. Basil Gary, 45 S. Dudley St., Lakewood, Colo. (*bfgh*) 58

Del Vecchio, Mr. Philip J., 971 E. 22nd St., Paterson, N. J. (*cd*) 58

Del Villar, Mr. Gabriel Ferrer, Av. Ruiz No. 482, Ensenada, Lower California, Mexico (*ceg*) 57

Dinger, Mr. Jacob E., Code 7110, Naval Research Lab., Washington 25, D. C. (*bcde*) 57

Ditto, Mr. Frank H., MIT-Lincoln Laboratory, Lexington, Mass. (*c*) 57

Dooley, Mr. James C., Castle Rd., Warrandyte, Victoria, Australia (*abdh*) 57

Dougal, Mr. Merwin D., Natural Resources Council, Statehouse, Des Moines, Iowa (*cg*) 58 S.M.

Dragoun, Mr. Frank J., P. O. Box 741, Hastings, Nebr. (*g*) 58

Drew, Mr. Howard R., 6124 Kenwick Ave., Fort Worth, Texas (*ceg*) 57

Drummond, Mr. Andrew J., Eppley Laboratory, Inc., 12 Sheffield Ave., Newport, R. I. (*c*) 57

Dugan, Mr. James T., 245 East 21st St., New York 10, N. Y. (*e*) 57

Duncan, Mr. John K., Division of Oceanography, U. S. Navy Hydrographic Office, Suitland, Md. (*def*) 58

Earle, Mr. Robert A., U. S. Coast & Geodetic Survey, Washington 25, D. C. (*acd*) 58

Ebling, Mr. John L., 9415 S. E. Mill St., Portland 16, Ore. (*g*) 57

Eckelmann, Dr. Walter R., Carter Research Laboratories, 1133 N. Lewis St., Tulsa, Okla. (*ef*) 57

Elder, Mr. Robert B., P. O. Box 7099, College Station, Texas (*e*) 58 S.M.

England, Mr. William R., R. D. 1, Williamsburg, Pa. (*bdg*) 57 S.M.

Evans, Dr. John Wainwright, Sacramento Peak Observatory, Sunspot, N. Mex. (*a*) 57

Fahlquist, Mr. Davis A., 216 Westgate, West, Cambridge 39, Mass. (*eh*) 57 S.M.

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Special Announcements

Back *Transactions*—AGU always welcomes the receipt of *Transactions* that have served their purpose in the hands of members and offers to pay postage involved in the return of these. Special need arises from time to time for certain ones. At the present time, copies of February, 1957, are especially requested.

Symposium on Snow and Glaciers—The International Association of Hydrology is to have a Symposium entitled "The Physics of Ice Movement," which will be held in Chamonix, France, September 16–24, 1958. Ralph N. Wilson, 3322 Stanford Street, University Hills, Hyattsville, Maryland, Secretary of the Section of Hydrology, AGU, is serving as a clearing house on these matters for U. S. Citizens. Others should get into touch with their respective national committees or with the Secretary of the International Association of Hydrology, L. J. Tison, 61 rue des Ronces, Gentbrugge, Belgium.

Pacific Northwest Regional Meeting to be Held in Portland, Oregon, November 13–14, 1958—The Pacific Northwest Regional group will hold its annual meeting in Portland, Oregon, November 13–14, 1958. Interested persons should get into touch with the present Chairman, Norbert Leupold (P. O. Box 5082, Portland, Oregon), or the Chairman-elect (takes office July 1, 1958) Wilbur D. Simons (U. S. Geological Survey, 207 Federal Building, Tacoma 2, Washington).

Pacific Southwest Regional Meeting—Plans are developing for the Pacific Southwest Regional Meeting to be held most probably at Stanford University, California, in January or February 1959. Interested persons should get into touch with the Chairman of the Regional Committee, Vito A. Vanoni, California Institute of Technology, Pasadena 4, California.

Fortieth Annual Meeting—The Fortieth Annual Meeting of the American Geophysical Union will be held in Washington, D C., in the week following the meeting of the National Academy of Sciences, probably May 4–7, 1959. If the National Academy meeting date is changed, we will adjust our meeting to meet in the week following, as is our usual custom. Watch these Special Announcements for further word.

Twelfth General Assembly, IUGG—The Twelfth General Assembly of the International Union of Geodesy and Geophysics will be held in Helsinki, Finland, July 25 to August 28, 1960. It is not too early to begin to lay your plans to attend this important gathering. Interested persons who are citizens of the United States should get into touch with the office of the American Geophysical Union, 1515 Massachusetts Avenue, N. W., Washington 5, D. C.

NATIONAL ACADEMY OF SCIENCES

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IGY BULLETIN

A monthly survey by the U. S. National Committee for the International Geophysical Year. Established by and part of the National Academy of Sciences, the Committee is responsible for the U. S. International Geophysical Year program in which several hundred American scientists are participating and many public and private institutions are cooperating.

Blue Glacier Studies

The information on which this report is based was supplied by Phil E. Church, Chairman, Department of Meteorology and Climatology, University of Washington, and Robert P. Sharp, Chairman, Division of Geological Sciences, California Institute of Technology.

Glaciers are among the most sensitive climatic indicators in nature: the snow and ice strata deposited from year to year provide a record of past climates and climatic fluctuations; and annual variations in accumulation and ablation (loss of snow or ice, primarily by melting) and advances and retreats of the ice front constitute keys to past and current climatic trends.

During the IGY, glaciologists and meteorologists of many nations are studying most known ice areas of the world, including both the great ice sheets of Greenland and Antarctica and a large number of valley glaciers from polar to equatorial regions. Ultimately, comparison of data accumulated through these worldwide studies will permit a better understanding of past and present epochal climatic variations. Moreover, implicit in an accurate knowledge of present trends are clues to future climates. The broad aspects of the US-IGY Glaciological Program are outlined in *Bulletin No. 2, August 1957*.

As part of the US-IGY effort to determine the present pattern and magnitude of shrinkage or growth of glaciers in the United States and Alaska, two teams of scientists are studying the Blue Glacier in the Olympic Mountains of Washington (Fig. 1) intensively. The University of Washington has established a permanent field station in the upper (accumulation) area of the glacier, and scientists of the California Institute of Technology are working in the lower (ablation) area of the glacier during the summer.

The University of Washington team is studying the mass budget of the glacier, the balance between the snow and ice accumulated and that lost by melting and erosion. This is primarily a meteorological study. The Caltech group is investigating the three-dimensional geometry of the Blue Glacier, its surface velocity, and the distribution of velocity with depth.

Blue Glacier itself is a small valley glacier

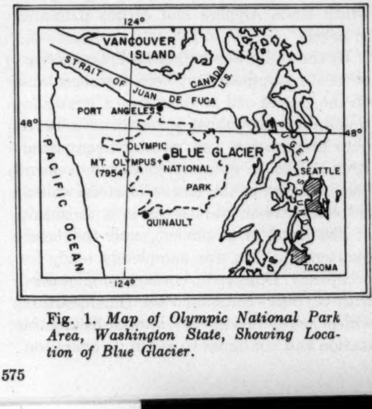

Fig. 1. *Map of Olympic National Park Area, Washington State, Showing Location of Blue Glacier.*

draining from snow fields on the northeast slope of Mount Olympus (47°47′N, 123° 42′W), which lies within the Olympic National Park. It is 2.5 mi long and 0.7 mi in maximum width. Although most of the world's glaciers are retreating at present, Blue Glacier is thought to be growing larger. Most of its accumulation area lies between elevations of about 5900 and 7600 ft above sea level on the 7954-ft mountain.

University of Washington Studies

The University of Washington station is located on a rock outcrop adjacent to the "Snowdome," a domed portion of the accumulation area in the upper part of the glacier, at an elevation of about 6800 ft. This station was established in June 1957. During the next two months a permanent building was erected for use as a headquarters and, nearby, a generator shack, meteorological building, and storage facilities for explosives were also constructed. A "fire cache" was constructed near the camp to hold emergency supplies and equipment to provide shelter in the event of fire or loss through natural disaster. Building materials and supplies were air-dropped by the US Air Force, and scientific equipment was brought in by Air Force and Coast Guard helicopters. The station is also supported by weekly flights of a ski-wheel-equipped light plane which lands supplies and carries personnel in or out.

By the end of September 1957, the meteorological equipment had been installed both on the glacier and at the camp, a triangulation survey to establish a control network for map preparation was virtually completed, 18-ft stakes to measure glacier movement had been set in the cirque (a steep-walled, amphitheatre-shaped recess in a mountain at the head of a glacier), and the headquarters building was completely ready for occupancy. Daily radio contact is maintained with Olympic National Park Headquarters, which cooperated greatly in establishing the station and continues to aid in its operation.

The station was manned by four men from July to September 30, 1957. Beginning on September 1, the winter schedule went into effect: two men remain at the station while the other two work at project headquarters at the University of Washington reducing and analyzing data. The two-man teams alternate each month.

The office work performed at the University of Washington includes reduction of solar radiation data, preparation of a sketch map, and estimate of the 1957 glacier budget. Snow temperature and time profile plots have been worked out for all data collected through the end of December 1957. Some data reduction and survey computations are also done by the field party.

Standard weather observations began in July 1957. The weather data obtained are transmitted daily to Port Angeles by radio. Snow records, obtained daily when weather permits, include amount of snowfall, water equivalent of snow, crystal type, surface densities, and the temperature profile in the surface layers.

Precipitation: Through January 1958, weather records suggest that the wettest part of the continental United States may be on Mount Olympus, near Blue Glacier. It was formerly thought that the Spruce-Quinault area, near the southern border of Olympic National Park, receives the maximum annual precipitation in the United States. However, in the period August through December 1957 there were 61.25 inches of precipitation at Spruce and 45.61 inches at Quinault, while the Blue Glacier Station measured a total of 67.90 inches. Moreover, high winds in November and December may have prevented the rain gauge from recording all the precipitation that fell. The total precipitation through February 1958 was 125.82 inches.

In general, precipitation increased greatly from summer into the fall and winter months—from 5.03 inches in August to 30.44 inches in January. The late fall and winter precipitation fell mostly as snow;

there were 49 inches in November, 118 inches in December, and 120 inches in January. Precipitation was recorded on 24 days in December and 18 days in January. During December, all but one of the 18-ft movement stakes set in the cirque were completely buried. By the end of February the gauges registered 417 inches of new snow; the depth of new snow remaining on the Snowdome was 207 inches.

The liquid water equivalent of the snow falling on Blue Glacier is unusually high. Although falling snow does not generally exceed 10% liquid water equivalent, the snow that fell near the camp in December averaged 25%. An interesting related feature of the new snow during the season at Blue Glacier, samples of which are taken every 24 hours, is its persistently high density. (Generally this was found to be greater than 0.20 gm/cc. Even short-term samples, collected at intervals of one or two hours, have seldom fallen below a density of 0.15 gm/cc.) An important cause of these high densities appears to be the strong predominance of needle crystals (Type 4 of the International Snow Classification) in many snowfalls. The geometry of these crystals can produce snow of high density.

Winds: Wind velocities were generally high and progressively greater, with some fluctuation, throughout the August-through-January period. In September, winds up to 80 mph were recorded on two days. Although it was somewhat less windy in October, so-called damaging winds—winds with velocities greater than 50 mph—were frequent thereafter, occurring on almost half the days during December and January. Winds of more than 100 mph occurred on at least five days in November (some observations were lost because of anemometer failure) and on two days in January; on one occasion, gusts up to 130 mph were recorded.

Temperatures: In August, temperatures averaged 34.9°F. September and October were exceptionally warm months for the Blue Glacier region, averaging 42.3°F and 32.9°F, respectively. During December, temperatures were usually between 20°F and 30°F, with a low of 8°F for the latter half of 1957 occurring in that month.

Snow-Ice Budget: Owing to the abnormally warm weather through early fall, ablation continued during much of October; only six inches of new snow remained on the Snowdome at the end of the month, although 22 inches had fallen.

Although ice-budget studies have been sporadic because of the difficult and time-consuming logistic problems, preliminary results appear to show a slight deficit since last year. This is probably a consequence of light snowfall during the previous winter combined with high summer ablation that persisted longer than usual. Periods of heavy ablation resulted from warm summer storms with high winds. The last of the snow cover accumulated in the 1956–1957 winter season disappeared from the vicinity of the station in early September, whereas about 10 ft of snow had existed at the end of the previous year's ablation period. Snow accumulation in the upper cirque is also lighter than last year's; the maximum observed depth of 1956–1957 winter snow cover remaining in the upper cirque was 16–20 ft in mid-September. Photographic records of new snow-crystal types are obtained whenever a new snowfall occurs.

Movement: It was hoped that it would be possible to resurvey the movement stakes at 15-day intervals to establish the amount and rate of movement of the glacier. This schedule is difficult to keep during the mid-winter months, however, as the number of days on which activity on the glacier is possible is limited by heavy storms, often of blizzard intensity, and by the danger of avalanches along the route to the cirque.

Snow Temperature: A snow settlement gauge is in operation and temperature studies of snow and firn (old snow that has lasted through at least one summer) are proceeding according to schedule. Significant results are being obtained. Winter chill, or sub-freezing temperatures, penetrated to a depth of about 10 ft in the firn by mid-February; the rate of penetration slowed progressively, and greatly, owing to the heavy insulating blanket of new snow.

A probe 50 cm long with thermocouples attached is used to obtain shallow temperatures in the snow and firn; for deeper temperatures, a 50-foot thermocouple cable was sunk into the glacier by hot point drilling. This cable extends to the isothermal layer.

Additional Studies: One new phase of investigation added after the program was under way is an extensive study of snow and ice albedo (percentage of light reflected by the surface), with emphasis on reflected solar radiation measurements made from a light aircraft. If possible, it will be carried out during the summer of 1958. Another, currently in progress when conditions are suitable, consists of time-lapse, photographic studies of cloud formation and development using a 16-mm movie camera. The Snowdome has proven to be an excellent "grandstand" for observing these cloud phenomena. In addition, microbarograph records are being collected for study of passages of fronts, and snow samples are obtained for oxygen isotope analysis at Caltech.

Solar radiation records have been obtained almost continuously but net and total radiation records have been irregular owing to frequent heavy formation of rime (opaque, granular, hard ice that forms on the upwind side of solid objects by freezing of supercooled cloud or fog droplets). This renders the radiometers inoperative for days at a time.

Caltech Studies

The work of the California Institute of Technology team is concerned only with the lower part of the ice stream, from the firn limit (lower limit of the accumulation area) to the terminus. It is hoped that these studies will yield basic information on the geometry and strain rates of Blue Glacier that will permit derivation of a basic flow law for valley glaciers.

The length of this segment of the glacier is 1.1 mi and the width is 0.6 mi. Like the University of Washington field party, the Caltech group received logistic support from the US Air Force and Coast Guard, and is aided materially by the National Park Service. The ski-wheel-equipped light aircraft is also used for resupply.

During the 1957 summer season the Caltech field party spent most of its time setting up experiments that will not yield maximum results until the 1958 season. However, some preliminary results have already been obtained.

Seismic Work: In the summer of 1957, thirty-five seismic stations were occupied on the ice tongue in the lower portion of Blue Glacier. Two of these stations were used solely for refraction and the remainder for reflection studies. A total of 144 records were made, of which two-thirds are expected to yield recognizable reflections.

At most stations the geophones were spread in both transverse and longitudinal orientations with respect to the glacier. Badly crevassed ice almost invariably gave poor results. At some stations no recognizable reflections could be obtained with transverse spreads, whereas excellent reflections were recorded with longitudinal spreads. This suggests that the floor beneath Blue Glacier may be very irregular on a small scale, thus complicating the reflection pattern.

The greatest ice thickness recorded during these seismic studies was about 920 ft, near the center line of the glacier a little below the firn limit. When carefully analyzed, the reflection records obtained along eight transverse profiles across the glacier should provide considerable information on the depth, slope, and configuration of the subglacial rock floor. Data are meager, however, for portions of the glacier near the lateral margins, because of crevasses, thinness of the ice, and complications arising from reflections from the valley walls. Seismic refraction records indicate a wave velocity of 3650 m/sec within the ice.

Movement: To obtain movement profiles, eight transverse lines of stakes were set from just above the lower edge of the glacier to slightly above the firn limit. The stakes, of which 49 were used, were set at an average depth of about 10 ft in the ice. Their positions were determined by theodolite measurements with reference to a system of accurately located fixed points on bedrock and stable moraines along the sides of the glacier. Subsequent resurvey indicates the rate of flow of different parts of the glacier. Preliminary data suggest a maximum velocity along the flow centerline of about six inches per day. Ablation of the ice at these poles was close to 12 inches per week during August 1957, and was uniform over the entire glacier below the firn limit. The stakes will be resurveyed again in the summer of 1958. The resulting data are expected to give the actual flow vector and permit calculation of its various components. Stratigraphic studies of firn were made in two pits, one on the lower glacier and the other on the Snowdome.

Attempts were made to drive boreholes to the bottom at two separate but nearby locations on the glacier. Inclinometer surveys to measure deformation in pipes left in the holes permit construction of vertical profiles of glacier velocity. Neither borehole succeeded in reaching the bottom, but valuable data are expected.

Inclinometer surveys have been made at about 25-ft intervals in both boreholes. Such surveys will be repeated for several years, as long as the holes remain open and unobstructed. One hole, drilled where the ice is thought to be about 900 ft thick, reached a depth of 400 ft. The other, 500 ft up-glacier along the same flow line, reached a depth of 738 ft at a point where the glacier is judged to be 886 ft deep. Drilling became very slow in the deeper hole at about 690 ft, where it is surmised that a band or layer containing much rock debris was entered. Another attempt to drill to the bottom of the glacier will be made in the 1958 field season.

Ice fabrics and structure: Exploratory studies of ice fabrics, the patterns produced by the preferred orientations of ice crystals, were carried out on Blue Glacier during the 1957 field season. The studies had three objectives: a general survey of ice fabrics and their relationship to the easily visible foliation pattern expressed by bubble layers in the glacier ice; a search for possible relationships between ice type and fabric type; study of the lateral persistence and significance of "multiple-maxima-type" fabrics, consisting of numerous clusters of crystals whose optic axes are oriented parallel to one another.

At all localities from which specimens were studied, a well-defined preferred crystal orientation was found. Coarse, recrystallized ice in Blue Glacier apparently has multiple-maxima fabrics, which have also been observed in other glaciers. Multiple-maxima fabrics appear to persist over distances of at least 15 ft laterally, retaining many of their main features. Fine, firn-like ice has fabrics with a well-defined crystal orientation parallel to the c-axes persisting over broader areas. The c-axes lie perpendicular to the plane of foliation.

Structures on the surface of lower Blue Glacier, such as foliation, crevasses, faults, and drag folds, proved to be unexpectedly well-developed and clearly displayed. Of particular interest is a double spoon-shaped structure which appears from beneath the firn and seems to extend to the terminus of the glacier. Detailed mapping and investigation of this and other aspects of Blue Glacier structure are planned by the Caltech group for the 1958 summer season.

Seismic Studies in the Andes

It has been the customary view of geologists that mountains and high plateaus are supported by a substructure of lighter crustal rocks extending downward into the heavier rocks of the earth's mantle, causing mountains to "float" in an isostatic balance, much as icebergs float. Mountains are themselves part of the 30- to 40-km-deep crust of the earth—which is made up of rocks such as lavas, metamorphosed sediments, and granites; these, through long epochs, are subjected to erosion, exposure and reburial, volcanic activity, and percolation of hot, mineralized solutions.

During investigations in the western United States in 1954, members of an expedition conducted by the Carnegie Institution of Washington found strong indications that another kind of substructure may also hold mountains up. A network of relatively narrow roots or veins of lighter crustal rock may project into the earth's mantle, the layer beneath the crust, to depths as great as 200 km. Since these diffuse roots are slightly less dense than the mantle rock, a crown of mountains—or an elevated plateau high above sea level—rises above them to equalize pressures, or maintain "floating equilibrium."

To test this idea elsewhere, the Carnegie Andes Expedition for the IGY during the summer of 1957 undertook investigations of the high regions of Peru, Bolivia, and northern Chile. In this work, they were aided by colleagues from the University of Chile and from San Marcos University in Peru. Their immediate aim was to attempt to determine the character of the roots of the Andes by measuring the waves from explosions used in the great open-pit copper mines of Peru and Chile.

(Compressional elastic waves, such as those generated in the earth by earthquakes or explosions, show a velocity of 5.6–6.1 km/sec in the lighter crustal rocks of the earth. Below the crust, an abrupt transition zone called the M-discontinuity (Mohorovičić discontinuity) is found in most places. Beneath this, in turn, are the heavier rocks of the earth's mantle, in which velocities range from 7.8 to 8.3 km/sec for compressional elastic waves.)

Members of the 1954 Carnegie field party in Arizona, New Mexico, and Utah had discovered that the thickness of the crust—as shown by strong reflections of compressional waves from the upper surface of the mantle—is about the same under the high Colorado Plateau as under the much lower plains and mountains of the eastern United States. This thickness of crustal material, 29 to 34 km, was also found under still higher Alaskan mountains on a 1955 Carnegie Expedition.

Two areas of the globe other than the Colorado Plateau region are characterized by a huge mountain bulk supporting an extensive elevated plateau—the Himalayas in Tibet and the Andes of southern Peru, western Bolivia, and northern Chile. The Andes, where thousands of cubic miles of rock rise to form a tremendous 12,000- to 16,000-ft plateau called the altiplano, were chosen as the site for a continuation of these studies.

In several of the Peruvian and Chilean copper mines single shots of 40 to 60 tons of dynamite are exploded almost every day. These explosions produce elastic waves, especially compressional waves, which pass through the crustal rocks and the higher-velocity rocks of the mantle below the M-discontinuity. It was hoped that observation of these waves, both those travelling along lines parallel to the mountains and those travelling across and beneath the mountains, would provide some clues to the character of the deep-lying structures that support these towering mountains (see Fig. 2).

The expedition, consisting of eight men and six trucks, left Washington in July 1957 and assembled in Lima, Peru, on August 14. During the next three months its members made measurements and recordings at more than 200 carefully selected locations deep in the mountains of Peru, Bolivia, and Chile. Radio timing techniques were used for observing the waves from nearly 60 large explosions. Most of these explosions were at the Toquepala Mine of the Southern Peru Copper Corporation, about 60 miles northwest of Tacna; some were at the Chuquicamata Mine of the Chile Exploration Company, about 125 miles northeast of Antofagasta. Both of these mines are at elevations above 10,000 ft.

Detailed studies of the seismic records have not yet been completed, but the wave measurements indicate that the Andean structures are highly non-uniform. An unexpected difficulty was encountered: the 50-ton explosions were not large enough to permit outlining of the structures deep under the altiplano. Measurements of actual depths to the M-discontinuity by observing strong reflected waves were successful only in limited sectors along lines more or less parallel to the mountains. Suitable observations directly across the mountains were not obtained in spite of weeks of intensive effort.

The reflection waves passing under the altiplano were attenuated to an extreme degree, a situation never encountered in the work in North America. This extreme attenuation may have some connection with the volcanic structures in the Andes, probably indicating that the sharp initial wave pulse is converted to secondary waves at countless interfaces within the mountain structures. Many successive wave conversions then reduce the initial pulse to a long wave train of very low amplitude, which does not show on the instruments above the general unrest of the earth's surface.

By sustained and intensive search, instrument locations were found that were very quiet by comparison with those occupied previously in North America. Although in many places the instruments were capable of detecting vertical wave motions of less than ½ Ångstrom in amplitude (1 Å equals one hundred millionth of a centimeter), no waves were recorded in Bolivia, on the other side of the mountains at distances of 250–450 km from the explosion sites. The amplitude of a normal total reflection in this region would have been expected to reach as much as 600 Å. The reflections observed at comparable distances along the sides of the main bulk of the altiplano, roughly paralleling the mountains, reached amplitudes of 500–800 Å in both Peru and Chile, as might have been expected on the basis of the earlier work in the Rocky Mountains and Alaska.

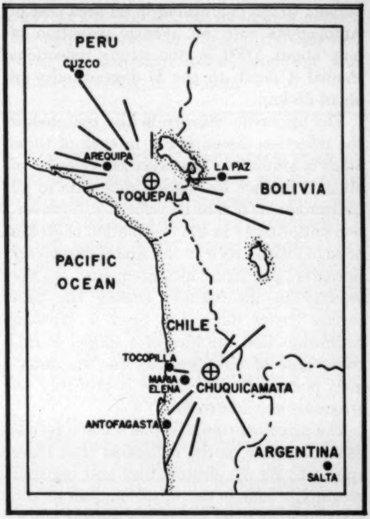

Fig. 2. *Regions in Peru, Chile, and Bolivia Investigated During Carnegie Institute Andes Expedition. Observations of Seismic waves from explosions in mines at Toquepala and Chuquicamata were made approximately along the radial lines.*

In Peru, beneath regions with average elevations of 9,000–10,000 ft, the depth to what appears to be the top of the mantle was found to be about 34 km, approximately the same as under the Rocky Mountains in the United States and Alaska. However, in northern Chile, again along lines roughly parallel to the mountains, in an area east of Antofagasta with an average elevation of only about 5,000 ft, the strong reflections showed a depth to the M-discontinuity of about 55 km.

The apparent velocity in the rock below the reflection discontinuity in each of these areas is similar to the expected velocity of about 8 km/sec for mantle rocks. As in all measurements of mantle velocities, however, non-uniformities in the overburden of 30 km or so of crustal rock in the Andes effectively prevents precision measurements of the velocity in the mantle. During the past several years there has been a growing realization that the idea of a single, world-wide value of wave velocity for the outermost portion of the mantle is probably an erroneous simplification.

The principal result of this seismic reconnaissance, then, is the indication that there appear to be non-uniformities and regional geographic differences in the mantle of the earth, just as there are in the crustal rocks. Under northern Chile, it appears that the lighter rocks of the crust project downward to nearly 55 km. This by itself is enough to float the mass of the Andes overhead. On the other hand, in southern Peru, the crustal rocks extend only to the normal depth of 34 km, and the towering Andes in that area are presumably held aloft by more diffuse roots projecting as much as 200 km into the mantle itself, or at least far below the levels where reflections of the explosion waves could have been observed.

Extensions of these observations of crust and mantle under the Andes may be made in the future by studies of local earthquake waves using a closely-spaced network of special seismographs. Further observations of explosion waves toward the coast are expected to be made during the IGY by the Geophysical Institutes of the University of Chile and of the San Marcos University in Peru using the Carnegie trucks and equipment, most of which were left in South America for this cooperative extension of IGY activity.

Rockoon Flights in the Atlantic, Pacific, and Antarctic Areas

This report is based upon material furnished by James A. Van Allen of the State University of Iowa.

From September 26 to November 9, 1957, thirty-six rockoons (balloon-launched rockets) were launched from the Navy icebreaker USS *Glacier*, as part of the US-IGY program. The first rockoon launching in this series was at 30°N in the Atlantic and the last was at 72°S in the Ross Sea adjacent to Antarctica. James A. Van Allen and Laurence J. Cahill, Jr., of the State University of Iowa (SUI) were in charge of the scientific portions of the program.

This work, together with earlier launchings in the Arctic in August 1957 (described in *Bulletin No. 5, November 1957*), constitutes a unified high-altitude investigation of cosmic-ray, auroral, and geomagnetic phenomena from 75°N to 72°S latitude.

The *Glacier* sailed from Boston on September 23, 1957, passing through the Panama Canal on September 30. It proceeded to the Line Islands area in the central Pacific, then sailed south, entering the Antarctic ice pack on October 31 at about 66°S, 178°W, and penetrating the pack to 72°05′S, 176°30′E.

Launchings were concentrated in the region of the Line Islands in the central Pacific, within the southern auroral zone in the south Pacific, and the Ross Sea. In addition, a series of flights was conducted along the ship's track, and two flights were made off the coast of New Zealand in a cooperative study with the low-frequency ionospheric station of Canterbury University College.

Arrangements for the rockoon-borne experiments were made with US Navy Task Force 43 by the IGY Inter-Service Coordinating Group. Through the courtesy of the Commander Task Force 43 and the Commanding Officer of the *Glacier*, substantial modifications of the sailing plan were made and extensive shipboard facilities and personnel assistance were provided.

Flight Summary

As in the earlier work in the Arctic, the Hawk rockoon vehicle was used (Fig. 3). The rocket was a modified Loki II solid-propellant unit with the experimental apparatus fitted to the forward end in a pointed cylinder, 3 or 3½ inches in diameter and about 38 inches in length. The payload (the weight of the instrument package) varied from 8 to 9.5 pounds. The rocket was suspended on a long load line beneath a 26,000-cubic-foot plastic balloon. It was fired by a barometric pressure switch when the balloon reached an approximate altitude of 23 km. The rockets reached altitudes of about 125 km. A tabulation of flights is given in Table 1.

All balloons performed satisfactorily, although two were damaged during inflation and were discarded. Of the 36 rocket-launching attempts, 20 can be considered normal flights, with summit altitudes ranging from 105–135 km. Seven rockets did not fire; two performed erratically; six were lost owing to equipment failure; and one was lost at launching, in a squall.

Objectives and Results

A major purpose of the rockoon program is measurement of total cosmic ray intensity over a wide range of geographic and geomagnetic latitudes during the present period of high solar activity. Special points of interest are (i) comparison of the intensity at upper atmosphere levels in high southern latitudes with intensity at high northern latitudes, and (ii) investigation of the location of the latitude "knee" (the geomagnetic latitude at which the number of incoming particles appears to fall off sharply) in the southern hemisphere.

Satisfactory cosmic ray intensity measurements up to an altitude of 23 km were obtained in a total of 15 flights distributed along the ship's track from 25°N to 72°S. On four flights (Nos. 52, 76, 84, and 85) satisfactory intensity data at upper atmosphere levels were obtained. These flights were made in many latitudes, but a variety of equipment failures caused a gap in the measurements in the vicinity of 30°S.

By January 1958, five sets of flight data had been read and reduced. They indicate that the total cosmic ray intensity at upper atmosphere levels in high southern latitudes is within 5% of that in high northern latitudes, and about 4.3 times as great as that near the equator. They also show that during the present period of high solar activity the

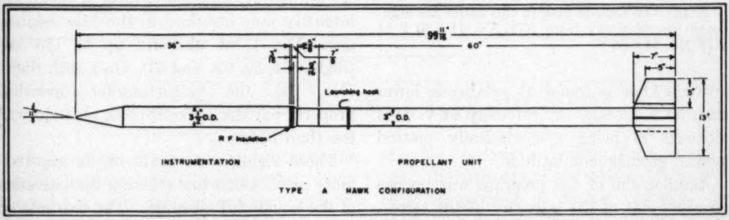

Fig. 3. Modified Loki II Rocket Used in Rockoon Experiments

Table 1. *Tabular Summary of Hawk Rockoon Flights*
Equatorial-Antarctic IGY Expedition,
23 September–10 November 1957

Date	Time (UT)	Geographic Position		Type of Instrumentation
26 Sept	1705	30°37′N	74°09′W	Test flight
27 Sept	1312	25°20′N	74°24′W	CR
4 Oct	1916	05°28′N	89°29′W	CR
13 Oct	1815	02°10′N	143°08′W	CR
14 Oct	2116	02°16′N	150°23′W	PPM
16 Oct	2002	07°07′N	156°38′W	PPM
17 Oct	0009	06°28′N	156°55′W	PPM
17 Oct	0218	06°11′N	157°01′W	PPM
17 Oct	2001	03°56′N	158°07′W	PPM
17 Oct	2344	03°23′N	158°41′W	PPM
18 Oct	0935	01°52′N	159°55′W	CR
18 Oct	1943	00°48′N	160°32′W	PPM
18 Oct	2343	00°02′N	160°52′W	PPM
19 Oct	1850	02°05′S	161°05′W	PPM
20 Oct	0106	02°31′S	161°25′W	PPM
20 Oct	0357	02°50′S	161°28′W	CR
20 Oct	2011	06°34′S	162°10′W	CR
22 Oct	2231	17°42′S	163°24′W	CR
26 Oct	1947	39°04′S	165°59′W	CR
27 Oct	0246	40°27′S	166°11′W	CR
29 Oct	0013	50°43′S	169°39′W	CRA
30 Oct	2140	60°05′S	176°06′W	CRA
31 Oct	0029	60°44′S	176°38′W	CRA
31 Oct	1951	65°03′S	177°51′W	PPM
1 Nov	0100	65°38′S	177°38′W	PPM
3 Nov	2008	70°14′S	175°42′E	PPM
3 Nov	2324	70°48′S	175°50′E	CRA
4 Nov	0141	71°10′S	176°08′E	PPM
4 Nov	0347	71°28′S	176°45′E	PPM
4 Nov	0716	71°58′S	175°40′E	CRA
4 Nov	1852	70°51′S	173°33′E	PPM
5 Nov	0125	69°32′S	173°38′E	CRA
5 Nov	1913	66°35′S	174°37′E	PPM
5 Nov	2159	66°09′S	174°41′E	PPM
8 Nov	2043	48°18′S	173°55′E	CRA
8 Nov	2315	48°01′S	173°50′E	CRA

Code: CR —Cosmic ray instrumentation
PPM—Proton precessional magnetometer
CRA—Cosmic ray and auroral instrumentation.

Note: The rockets fired in this series are numbered consecutively from IGY No. II 5.50 F to IGY No. II 5.85 F.

latitude knee is found at a latitude lower than 50°S. Cosmic ray intensity at various altitudes is being systematically plotted against geomagnetic latitude.

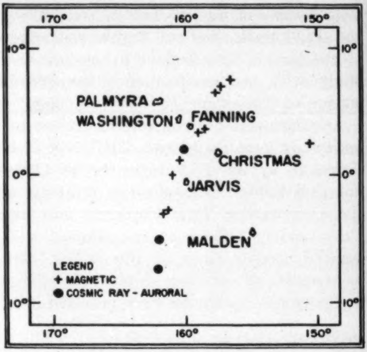

Fig. 4. *Line Islands Area, Showing Locations of Rockoon Flights.*

Another aim of the program was precise measurement of the intensity of the terrestrial magnetic field to altitudes over 120 km in the region of the equatorial electrojet. For these studies, a miniaturized proton precession magnetometer, designed at the State University of Iowa, was used. A detailed comparison of these data with simultaneous measurements made independently with variometers at the nearby IGY magnetic observatories on Palmyra, Fanning, and Jarvis Islands, in the Line Islands group, will be made. (These island observatories are operated by the Scripps Institution of Oceanography for the US Coast and Geodetic Survey and the Office of Naval Research.) Special interest was attached to the detection and measurement of electrical currents in the ionosphere by means of devices extending outward from the sides of the rocket. Such devices permit direct contact with the surrounding atmosphere.

Four satisfactory sets of data on magnetic intensity were obtained in the Line Islands area (Fig. 4) at altitudes up to 135 km (flights 54, 59, 62, and 63). On a fifth flight (No. 64), the magnetometer operated properly but the rocket's peak altitude was less than 70 km.

These flights were made on an approximate north-south line crossing the latitudes of the equatorial electrojet. The two sets of data which have so far been read indicate an

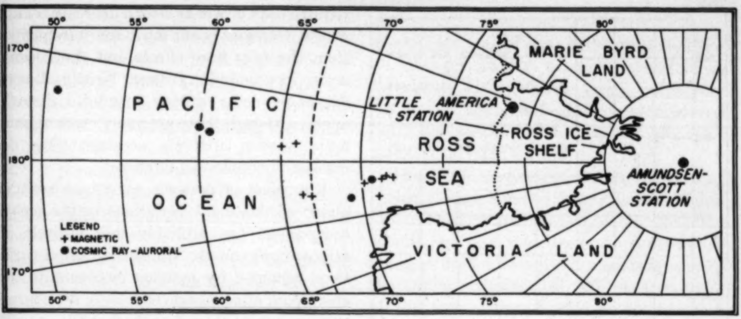

Fig. 5. *South Pacific and Ross Sea Areas, Showing Locations of Rockoon Flights.*

irregular, larger-than-normal decrease of 135 gammas in the total magnetic intensity, within the altitude range 97–121 km at 0° latitude. The absolute accuracy of each of a large number of measurements in this region is +5 gammas. Up- and down-leg data agree closely.

The data from flight 59, at 3°23′N, show a perceptible but markedly smaller discontinuity. The full reduction of all four sets of flight data obtained in the Line Islands area, when combined with the ground station measurements, are expected to yield illuminating information on the equatorial electrojet.

Several other experiments were conducted in the southern auroral zone. High-altitude measurements of the magnetic field were made for correlation with nearby Antarctic observations (Fig. 5). There were three successful magnetometer flights (Nos. 77, 82, and 83). Flight data have not yet been reduced. Investigations were made here of the physical nature, intensity, and latitude distribution of the "soft radiation" associated with auroras. Flight 76 (70°48′S, 175°50′E) was the only successful rocket flight of auroral instrumentation made in the zone. It encountered a high intensity of soft radiation resembling that studied extensively in the northern auroral zone during SUI rockoon expeditions from 1953 to 1957.

Precise absolute measurements of the intensity of the terrestrial magnetic field at sea level were taken at a number of new locations. Two new series of absolute values were obtained. The first series, in the Line Islands area, showed the current magnetic chart, No. 1703 of the US Hydrographic Office, to be correct within the limits of accuracy indicated. The second series of measurements, made in the Ross Sea, showed Chart No. 1703S, which was based on limited data, to be substantially in error in that region. The new values will be published shortly.

Variations in Cosmic-Ray Intensity

Observations of cosmic ray intensity at the earth's surface have long revealed many variations, both periodic and non-periodic. As noted in the report, "Thule Neutron Monitor Station," in *Bulletin No. 8, February 1958*, the intensity of the meson (heavy particle) component of cosmic radiation depends in a very complicated manner on the

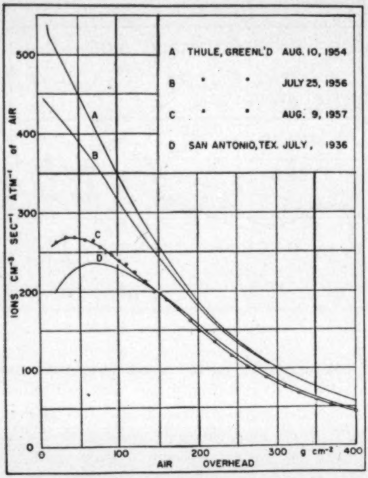

Fig. 6. *Cosmic-Ray Intensities in 1954 and 1956, Years of Low Solar Activity, Compared with Intensities in 1936 and 1957, When Solar Activity Was High. (Reprinted from* Physical Review.)

structure of the ever-changing atmosphere. A number of other intensity variations in both time and space are also observed. Some of these may give clues to the processes which produce and affect cosmic rays.

The largest of the observed variations in cosmic ray intensity are the rare increases associated with solar flares. At these times, neutron-monitor count rates may increase twenty-fold for a short period of time. Such flares have only been observed some half-dozen times.

Another non-periodic variation is the Forbush type of world-wide intensity decrease which occurs in association with some geomagnetic storms. In the Forbush-type decrease the cosmic ray intensity measured in ionization chambers may fall as much as 12% from the "normal" level. In neutron monitors the decrease may be as large as 2½ times this value, depending on the latitude of the station. Recovery to normal level may require days or weeks after a decrease occurs. These decreases occur much more frequently than the solar flare effects, but they do not occur in a periodic pattern. Nearly all such decreases occur during magnetic disturbances, although there are many cases of magnetic storms without accompanying decreases in cosmic ray intensity.

A number of periodic variations are also observed. Seasonal variations in the meson component are probably due entirely to atmospheric causes. The solar diurnal variations recorded by neutron monitors do not arise from atmospheric effects. A semidurnal variation is attributed to the fact that cosmic ray intensity is not the same in all directions.

During the very infrequent solar-flare increases, the variation in intensity may be as great as 25 times the level normally recorded. The decrease in intensity associated with geomagnetic storms may, as has been indicated, amount to as much as 30%. The solar diurnal variation has an amplitude of only 0.2%.

With the exception of the solar-flare increases, cosmic ray intensity variations at surface level are moderate. But investigations made prior to the IGY by H. V. Neher, of the California Institute of Technology, demonstrated that large changes do occur in the primary radiation arriving at the top of the atmosphere, especially in the north polar region. Over a period of years, Neher made observations near the north geomagnetic pole using ionization chambers carried by sounding balloons. His observations show that when the solar activity, as indicated by sunspot numbers, reaches a maximum in the eleven-year cycle the cosmic ray intensity decreases. This was also shown by results from the Carnegie Institution ionization chambers.

Near the north geomagnetic pole the flux of primary particles increased two-and-a-half times from the solar activity maximum of 1937 to the solar activity minimum of 1954. Most of this change was in protons at very low cosmic ray energies, below 10^9 electron volts.

This work has been continued in the IGY with balloon flights made during the summer of 1957 at Thule, Greenland. Figure 6 illustrates the large change that took place as solar activity increased during the cycle. Ionization due to cosmic rays at Thule during this period is reported by Neher and H. Anderson to be nearly 30% lower than during the solar maximum in 1937. They note that this is consistent with the higher level of solar activity during this cycle compared with the cycle of 20 years ago. In Figure 6, the rise of curve C above curve D at low pressures shows that more low-energy particles are present at high altitudes. Comparison of the results at Thule for the solar minimum of 1954 with those of August 1957 (near a maximum of activity) indicates that the total number of cosmic ray particles of all energies dropped by a factor of 4 in that period.

Observation of another variation during the IGY has been made with balloon-borne quadruple-coincidence counter trains launched at Swarthmore, Pennsylvania, under the supervision of M. A. Pomerantz, S. P. Agarwal, and V. R. Potnis, of the Bartol Research Foundation, for the purpose of detecting primary cosmic rays. When such flights were conducted during the period of general decrease of solar activity, 1949–1952, no changes in the primary intensity—as measured with counter trains containing 7.5 cm of interposed lead—were observed (with the exception of the rare increases associated with solar flares).

This is no longer true during the present period of high solar activity. Balloon flights (July–October 1957) have shown that the cosmic ray flux sometimes decreases by as much as 25% below the normal intensity of the earlier experiments. Within the limits of the apparatus, no changes in counting rate were detectable at altitudes below 60,000 feet, but at the highest altitudes attained the intensity varied between the earlier "normal" value and the minimum value.

From preliminary analysis of the data, a 27-day recurring variation has been observed. It has been followed through four cycles. Presumably, this effect is associated with a solar phenomenon which modulates the primary cosmic ray flux and is related to the 27-day solar rotation period. Surface level variations with similar dependence upon the 27-day solar cycle have been established in the past, but were of greatly reduced amplitude.

Second and Third US-IGY Satellites

1958 Beta

The second US-IGY satellite, 1958β, was launched from Cape Canaveral, Florida, at 7:16 am EST on March 17, 1958, under the direction of the Naval Research Laboratory.

Launching: The launching vehicle was a three-stage rocket, the third three-stage rocket fired in the Project Vanguard test program. The first and second stages were liquid-fueled rockets, the third stage a solid-propellant rocket. The first and second stages were stabilized and steered by altering the direction of thrust of the rocket motors. The third stage was stabilized by spinning the rocket about its longitudinal axis prior to ignition of the third-stage motor, thus integrating and cancelling out directional errors. The launching vehicle is approximately 72 feet long and 45 inches in diameter at its base. It is finless and has a gross take-off weight of 22,600 lbs.

Satellite Characteristics: The satellite, actually a test "payload," is an aluminum sphere, 6.4 inches in diameter and weighing about 3¼ lbs. It carries two radio transmitters and has six antennas (Fig. 7).

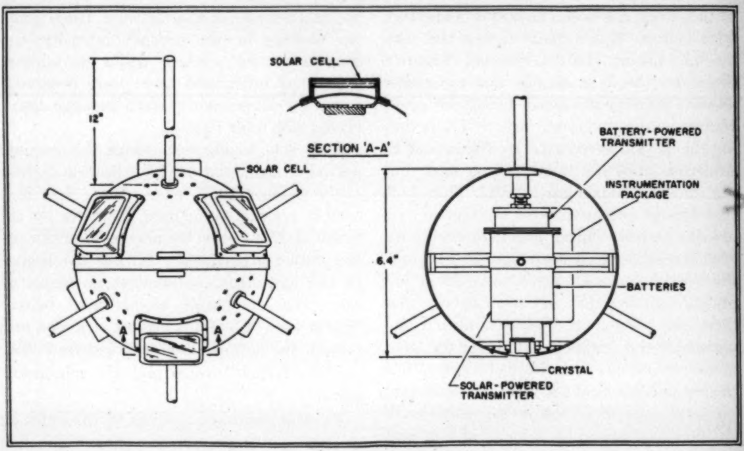

Fig. 7. Diagram of 1958β.

Instrumentation: Since the purpose of the test payload was to provide radio signals by which the rate of acceleration of the third stage could be determined and the efficiency of the separation mechanism checked, the test satellite carried no instrumentation other than the two radio transmitters. One transmitter, radiating 10 milliwatts at 108.00 megacycles, is powered by mercury batteries. This transmitter, which was expected to have a life of approximately two weeks, ceased operating on April 5th. The other, radiating 5 mw at 108.03 mc, is powered by solar batteries which have an indefinite life.

The frequency of each transmitter is controlled by a quartz crystal. Since changes in crystal temperature will cause changes in the frequency transmitted, temperatures at the crystal locations can be computed by measuring the changes in transmitter frequency. The crystal for the solar-powered transmitter is located just beneath the skin of the satellite; the crystal of the other transmitter is at the center of the satellite. Therefore, temperatures at these locations can be measured whenever the transmitters are in operation.

The solar batteries used were developed at the US Army Signal Engineering Laboratories at Fort Monmouth, N. J., under the direction of Hans K. Ziegler. They are a development of a solar battery first produced by Bell Telephone Laboratories in 1954.

Each battery consists of a series of 18 silicon cells, 1/400th of an inch thick; each cell contains two layers of silicon of differing electrical properties. When sunlight strikes a cell, electrons move from the positive layer (p-type) to the negative layer (n-type). The power thus made available to the 108.03 mc transmitter is approximately 40 mw.

Six solar batteries are spaced on the surface of the satellite so that at least one of the batteries will be in direct sunlight unless the satellite is in the earth's shadow. Because of the distance of the satellite from the earth, the satellite is expected to be in shadow only 15% of the time.

Orbit: The orbital elements for March 17 at 13 hrs 58 min 11 sec UT (the time of the first ascending node), as computed by the

Vanguard Control Center on March 18, were:

Period, 134.0 minutes; apogee, 2466 statute miles; perigee, 404 statute miles; inclination of the orbit, 34.1°; longitude of ascending node, 129.2°E; westward geographic motion of the node, 33.89° per day; latitude of perigee on descending branch, 26.1°N; eccentricity of orbit, 0.191; semimajor axis, 1.362.

Observations: Radio signals were received from the satellite on each pass until the battery-powered transmitter ceased operation. Since then, signals have been received only when the satellite is in sunlight.

The first sighting of 1958β was by a Moonwatch team at Alamogordo, New Mexico, on the morning of March 19.

1958 Gamma

The third US-IGY satellite, 1958γ, was launched from Cape Canaveral, Florida, at 12:38 pm EST, March 26, 1958, by a Jupiter-C rocket developed jointly by the US Army Ballistic Missile Agency and the California Institute of Technology Jet Propulsion Laboratory.

Satellite Characteristics: The satellite has essentially the same physical characteristics as 1958α (see *Bulletin No. 10, April 1958*), but does not carry a turnstile antenna with its four whip-like extensions. It weighs 31.00 pounds; this is 0.20 pounds heavier than 1958α.

Instrumentation: As in 1958α, the cosmic ray experiments carried in 1958γ were designed and installed by the Physics Department of the State University of Iowa (SUI) under the direction of James A. Van Allen. The micrometeorite experiments carried in both 1958α and 1958γ were designed and installed by the Geophysics Research Directorate of the Air Force Cambridge Research Center.

The instrumentation of 1958γ is slightly different from that in 1958α. The differences are: addition of a magnetic tape-recorder unit, designed by G. H. Ludwig of SUI, to record and store information on cosmic rays gathered through an entire orbit; addition of a radio to receive interrogation signals from ground stations; omission of the microphone for recording of micrometeoritic impacts on the satellite shell; omission of the temperature probe in the nose cone; and use of a dipole antenna, formed by dividing the shell of the satellite itself, in place of the turnstile antenna.

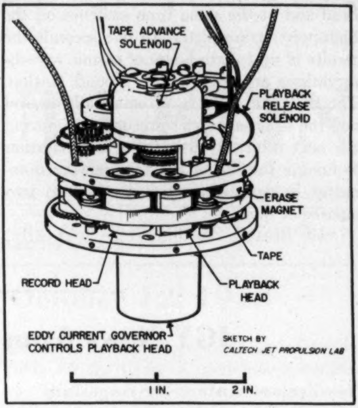
TAPE ADVANCE SOLENOID
PLAYBACK RELEASE SOLENOID
ERASE MAGNET
TAPE
RECORD HEAD
PLAYBACK HEAD
EDDY CURRENT GOVERNOR CONTROLS PLAYBACK HEAD
SKETCH BY CALTECH JET PROPULSION LAB
1 IN.
2 IN.

Fig. 8. *Magnetic Tape Recorder Used in 1958γ to Record Information and Transmit it to Ground Stations When Interrogated.*

1958γ carries two transmitters, identical to those in 1958α. The low-power transmitter, operating on 108.00 mc, transmits information continuously on skin temperature and internal temperature, micrometeorite counts as recorded by an erosion grid, and cosmic ray counts. The high-power transmitter, operating on 108.03 mc, transmits only when interrogated by a ground station, and sends only cosmic ray information recorded in the tape recorder memory unit (Fig. 8). It is interrogated each time it passes over the Minitrack network along the 75th meridian in North and South America. The signal from the ground station is picked up by a receiver; this starts the magnetic tape running over the playback head and at the same time switches on the high-power transmitter. In five seconds the results of up to two hours of cosmic ray observations are sent to the ground station. The magnetic tape is automatically erased and the recorder reset to record data during the next orbit. By using this interrogation technique the life of the high-power transmitter is expected to be extended to two months or more.

Orbit: Because the third stage fired early, before it had reached proper alignment, the orbit of 1958γ is more elliptical than that of any of the IGY satellites fired earlier. The approximate orbit as of March 28 was: Period, 115.9 minutes; inclination of orbit to the equator, 33.8°; perigee, 116.9 miles; and apogee, 1740.8 miles. This somewhat eccentric orbit is providing a scientific bonus for it gives a sweeping profile of cosmic ray information from relatively low to quite high altitudes.

IGY News from Other Countries

New Zealand Antarctic Symposium

Scientists of seven nations met in Wellington, New Zealand, February 18–22, 1958, at the invitation of the New Zealand National Committee for the IGY, to take part in an informal discussion of IGY work accomplished in the Antarctic during the preceding year. Nations represented in addition to New Zealand were Australia, France, Great Britain, South Africa, the USA, and the USSR. Two types of meetings were held: those of general interest at which informal papers were presented and discussed, and round-table discussions among delegates concerned with a particular discipline.

A list of symposium discussions, together with the chairmen of each, follows: Special Investigations in Glaciology, J. L. Zumberge, US; The Topography of the Sub-Glacial Continent, Bertrand Imbert, France; Geomagnetism, R. L. Viets, US; Logistic Support Problems in the Antarctic, M. A. F. Barnett, NZ; Meteorology, V. I. Rastorguev, USSR; Seismology, T. Hatherton, NZ; Biology, Botany, and Zoology, R. W. Balham, NZ; Oceanography, U. V. Cassie, NZ; Aurora, F. Jacka, Australia; Geology, R. W. Willett, NZ; Radiation and Micrometeorology, Herfried Hoinkes, US; and Future Research in the Antarctic, G. de Q. Robin, Great Britain.

Most of the delegates had just returned from the Antarctic and had not had the opportunity to prepare formal papers. The symposium permitted exchange of field results and discussion of items of interest affecting future work without the need to wait for publication of papers.

Participants in the symposium are now preparing papers covering the subjects discussed. These papers will be published by the New Zealand National Committee for the IGY in the near future.

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NATIONAL ACADEMY OF SCIENCES

Number 12 • June 1958

IGY BULLETIN

A monthly survey by the U. S. National Committee for the International Geophysical Year. Established by and part of the National Academy of Sciences, the Committee is responsible for the U. S. International Geophysical Year program in which several hundred American scientists are participating and many public and private institutions are cooperating.

Total Solar Eclipse: October 12, 1958

Since 1836 scientists have been making physical observations of the solar spectrum during eclipses, especially of the spectrum of the corona, the outer atmosphere of the sun (see Fig. 1). Invention of the coronagraph by Lyot in 1930 made it possible to observe some aspects of the corona without waiting for an eclipse; but the "artificial eclipse" of the coronagraph does not completely eliminate the scattered light from the sun's disk. In a total eclipse, radiation from the solar disk is blocked by the moon; for a short period, therefore, only radiation from the corona reaches an observer in the path of totality. Thus, an actual solar eclipse provides a unique opportunity to study characteristics of the sun and of solar-terrestrial relationships which cannot be duplicated in a laboratory.

Studies of the distribution of different radiation wavelengths on the sun's disk and the effects of specific wavelengths on the ionosphere are made possible during an eclipse since the moon acts as a shutter, successively blocking off portions of the disk. This effect cannot be duplicated by the coronagraph.

The total eclipse of the sun due on October 12, 1958, occurs at an extremely opportune time for solar studies; the solar physics studies of the IGY will provide an abundance of data on the sun for long periods before and after the eclipse. It also occurs near a period of maximum solar activity, the most active solar maximum in recorded history. September and October 1957, on the basis of preliminary reports, had the highest sunspot numbers ever recorded. At the time of the eclipse the sun should still be very active.

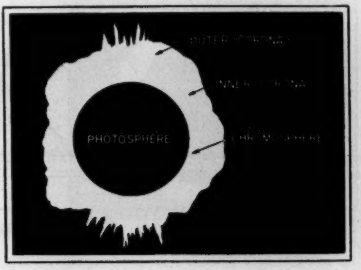


Fig. 1. *Solar Regions. The visible disk of the sun is called the* photosphere (*sphere of light*). *Above the photosphere is the* chromosphere (*sphere of color*). *The portion of the chromosphere immediately above the photosphere is sometimes called the "reversing layer." Above the chromosphere is the* corona (*crown*), *which is divided into* inner corona *and* outer corona, *or* white corona. *The boundaries between regions are not definite, one region merging imperceptibly into another.*

Observational Program: The Technical Panel on Solar Activity of the US National Committee for the IGY is taking full advantage of this favorable situation and has organized an extremely broad observational program. Six teams of US scientists will travel

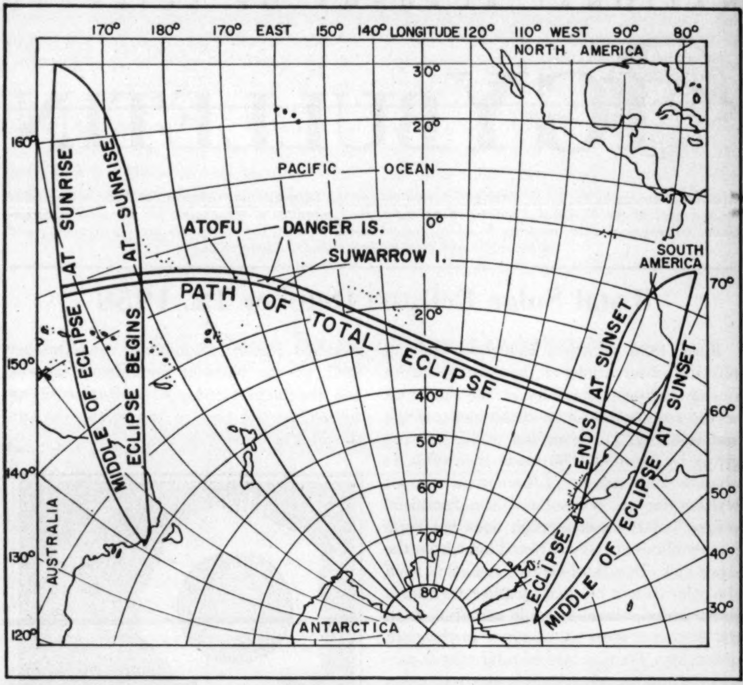

170°
180°
170° EAST
150°
140° LONGITUDE 120°
110° WEST
90°
80°
NORTH AMERICA
30°
20°
160°
PACIFIC — OCEAN
0°
ATOFU — DANGER IS.
SUWARROW I.
SOUTH AMERICA
70°
PATH OF TOTAL ECLIPSE
20°
150°
40°
60°
50°
140°
60°
50°
70°
130°
40°
80°
30°
120°
AUSTRALIA
ANTARCTICA
MIDDLE OF ECLIPSE AT SUNRISE
ECLIPSE BEGINS AT SUNRISE
ECLIPSE ENDS AT SUNSET
MIDDLE OF ECLIPSE AT SUNSET

Fig. 2. *Path of Totality of Eclipse of October 12, 1958, and Location of Observation Sites.*

to the Danger Islands, an atoll in the South Pacific also known as Pukapuka after the largest island in the group; there they will mount four ground-based optical experiments, one rocket experiment, and one ground-based electronic experiment. Preparations for these experiments have been underway since before the beginning of the IGY in July 1957.

Existing weather records indicate a 40% chance that clouds will obscure the sun during the critical period of totality, but cloud conditions will impede only the optical experiments. No matter what the weather, the electronic experiment and the rocket observations will go forward and should obtain extremely valuable data on solar radiation and associated ionospheric effects.

The institutions participating in the expedition are the Naval Research Laboratory (NRL), the Central Radio Propagation Laboratory (CRPL) of the National Bureau of Standards, the University of Wisconsin, the California Academy of Sciences, the US Naval Radiological Defense Laboratory, the Sacramento Peak Observatory, and the High Altitude Observatory.

Logistic Problems: The main problem facing the planners of the expedition has been the selection of a suitable piece of land on which to erect the observational instruments. The path of totality begins at sunrise approximately on the equator at about 158°E and ends at sunset at a point inland from Santiago, Chile (see Fig. 2). The path misses all the large Pacific Islands, and observations from Chile would be impractical because of the low altitude of the sun at the time of eclipse. The only dry land from which observations would be profitable are coral islands too small to support a large expedition comfortably.

The logistic problem has been solved with the help of the Navy, which is furnishing the USS *Thomaston*, a Landing Ship Dock (LSD), to serve as transportation, floating hotel, and warehouse for the period the expedition is at the Danger Islands site. The expedition plans to arrive at the Danger Islands about September 1 and leave on November 1. Except for a period of one week during which the *Thomaston* will travel to Samoa to refuel, all personnel will live aboard the ship. They will be ferried by boat and helicopter to and from the observational site on the most southerly island of the group, Motu Koe.

Since the *Thomaston* is much too large to enter the lagoon of the atoll by the only passage, and anchorage is not possible outside the atoll, the LSD must steam back and forth in the open ocean two or three miles from the outer reefs to maintain position.

Electronic Experiments

Two electronic experiments, one by the Naval Research Laboratory and one by the CRPL, National Bureau of Standards, will observe ionizing sources on the sun and the resultant ionization in the earth's atmosphere.

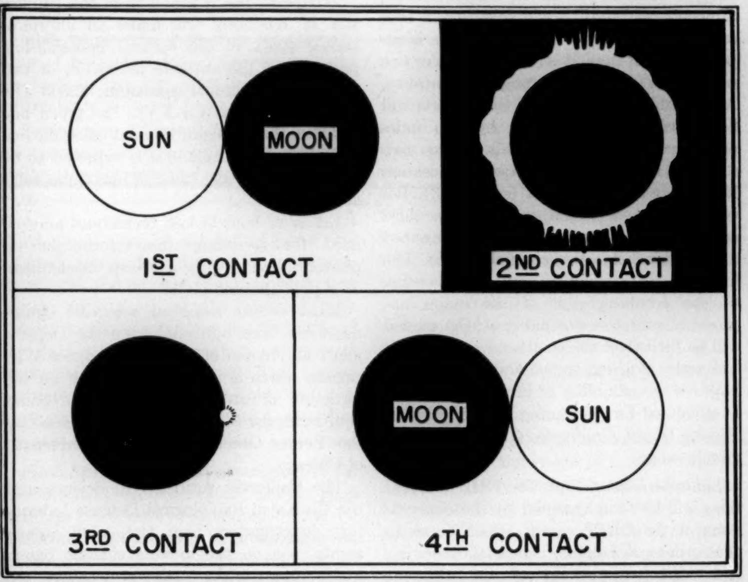


Fig. 3. *Progress of Total Solar Eclipse. The moon appears to overtake the sun in their passage across the sky:* (a) *The moon touches the edge of the sun (first contact);* (b) *The moon covers the sun and the corona becomes visible (second contact);* (c) *The sun reappears (third contact);* (d) *The moon passes the sun (fourth contact).*

Ionizing Sources: The Naval Research Laboratory plans to study the distribution of ionizing sources on the sun's disk and in the corona by direct measurement from rockets. NRL plans to fire a series of 6 to 8 rockets during the eclipse, two during the period of totality and the rest during the partial eclipse before and after totality. Each rocket will be equipped with detectors for soft X-rays (50 Å), harder X-rays (8–20 Å or 1–7 Å), and Lyman-alpha ultraviolet radiation (1216 Å). The rockets will be the Nike-Asp system, fired from shipboard approximately 10 miles from Pukapuka. Data recorded during the rocket flights will be telemetered to receivers aboard the *Thomaston.*

Each rocket will be in flight for approximately seven to eight minutes—about five minutes of which will be above the absorbing atmosphere. Totality will last about four minutes. As the most interesting data is expected at that time, it is planned to have two rockets in the air throughout totality. Aboard ship, data from the two rockets will be recorded simultaneously by two independent telemetering stations. These two rockets will be launched in quick succession just before second contact (see Fig. 3). Between first and second and between third and fourth contacts, rockets will be launched so as to bracket active coronal regions. The first in each pair will measure the solar flux as the occulting disk of the moon approaches an active coronal spot; the second will be fired after the spot is covered.

A series of firings to test and, if necessary, improve the reliability of the rocket system is scheduled for the spring of 1958 at San Nicolas Island, California, on the Pt. Mugu missile range.

Ionospheric Soundings: The NRL observations will be complemented by the observations of the CRPL group, which hopes to obtain data on heights, ionization densities, and critical frequencies of the different ionospheric layers by use of a modified vertical-incidence sounder. The sounder will operate from Motu Koe Island during the eclipse and for a suitable period before and after. Using pulses of radio energy, this equipment determines the heights and ionization densities of the ionospheric layers.

Because these layers are ionized by solar ultraviolet and X-radiation, a solar eclipse causes a marked decrease in ionospheric density. Correlation of the radiation data gathered by the rockets and the ionospheric data gathered by the sounder should give much information about the changes of ionospheric structure with changes in solar radiation. These two experiments can be carried on regardless of the amount of cloud cover.

Optical Experiments

Interferometry: A group from the University of Wisconsin will make an interferometric study of the coronal emission-line profiles and the absolute intensities of two lines of the coronal spectrum, $\lambda5303$ (Fe XIV) and $\lambda5694$ (Ca XV). The green line $\lambda5303$ is the strongest coronal emission line and the yellow line $\lambda5694$ is expected to be at its brightest at a time of maximum solar activity.

Either or both of two techniques may be used for recording the information: a photomultiplier with a sweep mechanism, or a photographic plate.

Most of the essential scientific equipment has been borrowed from the Department of Physics of the University of Wisconsin, where it is used in research on the structure of atomic spectral lines. Other equipment for the expedition was loaned by the Yerkes Observatory of the University of Chicago.

The California Academy of Science and the US Naval Radiological Defense Laboratory investigators plan two joint experiments, one on the moving shadow bands which appear in the earth's atmosphere just before second contact and just after third contact, and one on the polarization of the outer corona.

Shadow Bands: Measurements will be made of shadow-band phenomena by recording the output of photronic cells on a Helland Oscillograph Recorder during the period just prior to second contact and just after third contact. An array of 8 or 10 cells will be set up in some pattern as yet not wholly decided upon, but likely in the form of a cross, spaced at varying distances in an effort to obtain the direction, speed, and wavelength of the shadow bands. Each cell, measuring about 2 by 6 inches, will be mounted on a stake driven into the ground and connected to the recorder by a shielded cable.

Since it is generally believed that the shadow-band phenomena are produced by atmospheric discontinuities, it would be desirable to correlate the motions of the shadow bands with velocity and direction of winds aloft. It is hoped that NRL will be able to provide wind data by observations of balloons released sometime during the hour or two just prior to or just after eclipse time.

Polarization of Corona: A camera now under construction will employ a 20-inch focal length lens for obtaining photographs of the outer corona (white corona) in light polarized with respect to radial directions. A shutter consisting of a rotating sector will be used, and a sheet of polaroid will be rotated with the shutter. By an independent rotary adjustment of the polaroid with respect to the shutter, use can be made of the light polarized at various angles with respect to a radius. By use of filters, further restriction of the light can be obtained; this may provide added information regarding the polarization of the corona.

Flash Spectrum: A joint experiment of the Sacramento Peak Observatory and the High Altitude Observatory, sponsored by the US Air Force, will attempt to photograph the "flash spectrum" of the chromosphere. At the instant of totality the dark lines of the Fraunhofer spectrum appear to change suddenly to bright lines of chromospheric emission. The phenomenon lasts only a short time, perhaps 25 seconds at second contact and 25 seconds at third contact for the strongest lines, and the weakest lines may be observable for only 3 to 4 seconds in all. But observation of the flash spectrum yields information on structure and composition of the chromosphere which can be obtained in no other way.

In order to obtain the desired information on the corona, height resolution of the order of 100 km is necessary. This cannot be accomplished with a coronagraph, because errors of seeing in a man-produced "eclipse" blur height discrimination of distances far greater than 100 km. When the eclipse is produced outside the atmosphere, however, such height discrimination becomes possible—provided photographs can be taken fast enough. To do this, a spectrogram must be exposed every 0.3 second.

The equipment consists basically of a triple spectrograph to cover three spectral ranges: (1) 3300 Å to 6600 Å for the ultraviolet unit; (2) 3600 Å to 4900 Å in the visible; and (3) 5000 Å to 9300 Å in the infrared. Dispersions will be 5½ Å/mm in the ultraviolet and infrared and 2 Å/mm in the visible. The spectrographs will be fed by a single coelostat (a rotating mirror which follows the sun's movement). Each spectrograph will have a double camera unit, so that the speed requirement for a single camera will be one frame each 0.6 sec. Exposure is to be 0.2 sec, with film transport and shutter action to be accomplished in 0.4 sec. The size of each frame is 26″ by 7″.

Each frame will contain three separate spectra differing from each other in terms of intensity of the incident light in the ratio of 1 to 20 to 400. Also to be included on each frame will be the image of a step wedge illuminated by a lamp, to furnish a standard for comparison of the intensity of the spectra. Finally, there will be a serial number on each frame. The serial number will be used to identify the frame, so that it can be matched up with additional data (length of exposure, time, and so forth) to be imprinted on a multi-channel recorder. Absolute calibration will be provided by exposing spectra of the sun itself through the same optical system, both before and after the eclipse.

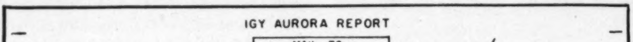
Expeditions by Other Countries

In addition to the US-IGY effort, at least two expeditions from other countries will conduct careful observations of the eclipse. The Japanese plan an extensive series of observations from a base on Suwarrow (Suvarov) Island, several hundred miles from the Danger Islands. The USSR has indicated that it will send an expedition but has not designated a site. New Zealand will establish a base at Atofu.

The Visual Auroral Program

Much of the following material has been adapted from a manual prepared by C. W. Gartlein and D. S. Kimball, Cornell University, for use in the IGY visual auroral program.

Auroras are the visible manifestation, in the earth's atmosphere, of a group of phenomena resulting from disturbances in the sun's interior and surface layers. They mark the paths within the atmosphere of the streams of solar particles ejected by eruptions on the sun. Hence, studies of the forms and global distribution of auroral displays do much to define these paths, as well as to determine the energies of the particles, the way they are trapped by the



IGY AURORA REPORT

42.5 N
LATITUDE

76.5 W
LONGITUDE

ITHACA, N.Y.
LOCATION

MAIL TO
IGY Auroral Data Center
Cornell University
Rockefeller Hall
Ithaca, N.Y.

APR.
MONTH

6/7
NIGHT

1957
YEAR

21
HOUR

15
MINUTE

75 +h
TIME ZONE

NO AURORA IN SKY ☐ MEASURED ☑ OVER ☑

C.W. GARTLEIN
OBSERVER

Fig. 4. *Sample Auroral Report on Standard Graphic Card. The report, for 9:15 pm EST, shows a medium-intensity homogeneous arc (HA) extending from the western horizon to a bank of clouds 30° above the eastern horizon. As no color is indicated, the arc is either colorless or yellow-green. The HA reaches an angular height of 80° from the northern horizon—almost to the observer's zenith. To the north and at a height of 50° is a bright, eastward-drifting rayed arc (RA). Its lower margin is red. Rays (R) of medium intensity appear toward the northwest. They are vertical and extend from 8° to 20° above the horizon. No aurora appeared in the south. More elaborate sketches, or simple letter symbols, may also be used on these cards.*

earth's magnetic field, and possibly their acceleration within the atmosphere.

While auroras occur most frequently in high latitude belts circling the geomagnetic poles, auroras visible in middle and low latitudes, and especially in the tropics, are of special scientific interest. During the IGY, auroral displays in these regions in the northern hemisphere are being studied intensively by a large number of visual observers throughout the US and Canada.

Thousands of visual observations of auroras have been made in the past but systematic analysis in terms of form, time, location, height, extent, intensity, movement, etc. has been lacking. The IGY Visual Observation Program is designed to correct these deficiencies.

North American IGY Visual Observation Program

In the integrated, cooperative North American IGY program for visual auroral observation, personnel at meteorological stations of Canada and the United States are supplying much of the data. As other duties permit these participants to observe for short intervals only, many volunteer observers have been asked to assist. The volunteers are able to make more continuous and detailed observations than time allows the meteorological observers. Airline and ship crews are also assisting in the program.

In past visual observation programs, many observers have supplemented their written reports with sketches to show details of the arrangement of auroral shapes, structures, and movements. In one program the entire report was made in sketch or graphic form. This method was so satisfactory that it is used as the basis of the present volunteer program.

Reports are made graphically on a simple card which carries a diagram consisting of four quadrants representing the dome of the sky as seen facing south, west, north, and east (see Fig. 4). Completed reports are mailed to the IGY Auroral Data Center at Cornell University, Ithaca, New York.

Auroral Forms and Sequence

Auroras occur in a number of characteristic forms (Fig. 5), for which simple graphic representations have been standardized to facilitate reporting.

The various auroral forms usually occur in a specific sequence during a particular display, although the entire sequence may

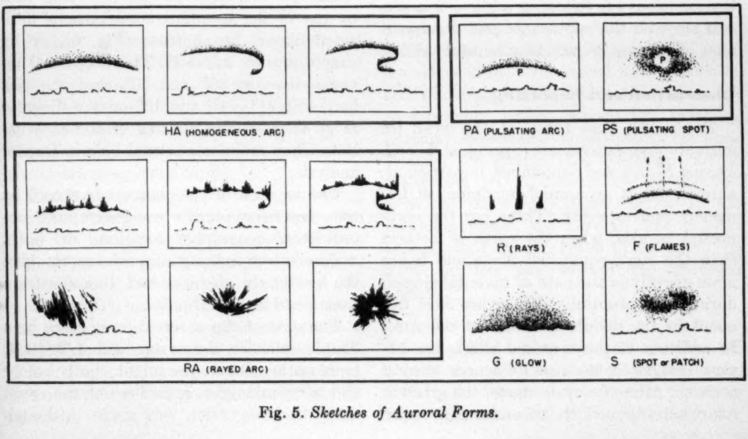


Fig. 5. *Sketches of Auroral Forms.*

not necessarily appear. Near the beginning of a display, predominantly homogeneous forms appear, glows (G) and homogeneous arcs (HA). There is little motion. A glow seen early in a display may actually be the upper part of a distant aurora whose lower border lies just below the horizon. The aurora may subsequently rise, revealing itself as an arc or a band. This may be repeated more than once.

Rayed forms showing considerable motion are characteristic of the second phase of the display. This phase, consisting of rayed arcs (RA), rays (R), and sometimes flames (F), is the main part of the display. It is accompanied by increased luminosity and the appearance of distinctive colors.

The declining phase of the auroral display is characterized by indistinct patches of luminosity, sometimes spotty (S) and with scattered, diffused rays; glows, which may persist for several hours; pulsating forms (P); and occasionally rays or flames.

Changes in auroral forms during a display are believed to be associated with changes in the earth's magnetic field, earth currents, and ionosphere. Of particular interest are changes of one form into another, such as a homogeneous arc into a rayed arc; the appearance of a new form, such as a homogeneous arc following a glow, or a second arc; and the appearance and disappearance of flaming or pulsating auroral forms.

Observation and Reporting

Time: The best times of the year for auroral observations are Spring and Fall. During March and September, in particular, auroras are at an annual maximum of frequency and intensity. These are the equinoctial periods, when the earth is farthest from the sun's equatorial plane and hence more directly in the path of material ejected during solar eruptions. (These are most frequent in the middle latitudes of the sun.) In addition to this seasonal effect, the 11-year sunspot cycle also influences auroral activity. After the cycle starts, the greatest solar activity, which means many solar eruptions, occurs in middle solar latitudes. Later in the cycle, although eruptive activity takes place nearer the sun's equator, such activity diminishes considerably. As a result of the combined effects of these seasonal and cyclical factors, auroral activity reaches a peak about a year after the sunspot maximum.

Although auroras are usually more frequent during the periods March–April and August–September, observation is not restricted to these months. Northern observers make observations each possible night throughout the year. A report of no aurora on a clear night may be as important statistically as the record of a brilliant display, particularly during times of Alerts and Special World Intervals (SWI) declared by the IGY World Warning Agency (WWA). (*Bulletin No. 5*, November 1957, contains an outline of the IGY Special World Days Program for coordinated intensification of upper atmosphere observations during times of heightened solar activity.) In latitudes below about 40°N, where auroras are rare, observations are made primarily on nights when geomagnetic disturbances are expected, i.e., during Alerts and SWI.

Reporting auroral forms: The auroral forms are indicated on the reporting card by use of the standard abbreviations indicated above, by sketches (Fig. 5), or by simple graphic symbols. The horizontal division lines at 30° and 60°, and the tick marks at 21°, 14°, and 10° on the diagram (Fig. 4) guide the plotting of the observation. They are also essential aids in further analysis.

The location of the observer is shown on the reporting card by geographic coordinates, geographic location, or both. Airline crews making auroral reports give the location by distance and direction from some nearby control point.

The date of the observation is given as a double calendar date, e.g., Jul 1/2 1957, representing the entire night, both before and after midnight, regardless of the exact time the observation was made. Although regular observations are made as nearly as possible every quarter hour, the exact time of an observation is recorded to the nearest minute on a 24-hour basis, e.g., 23^h42^mEST or 2342EST.

Visibility: Clouds, haze, fog, twilight, moonlight, and other factors affecting light conditions in the sky determine the visibility of a given aurora. They also affect it indirectly by changing the brightness of distant city glow. Such conditions are recorded in the diagram by circled abbreviations.

Location: When the lower border of an auroral form, generally about 100 km (62 mi) above the earth's surface, is seen 60° above the horizon, the form is located over a point on the surface about 30 mi from the observer. Thus, the upper ⅓ of the quadrants on the diagram contain reports of auroras occurring within a radius of approximately 30 mi of the observer's location. Similarly, the 30° lines define a circle with a radius of about 90 mi centered on the observer. The short tick marks represent lower elevations above the horizon and define circles of greater radii. In this way, a complicated mathematical transformation is effected in a simple, graphic manner with the required precision.

Heights of auroral forms: Measurement of the angular height of an auroral form is made by visual estimate or by use of devices for determining vertical angles, such as theodolites, air navigation octants, inclinometers, and alidades. Forms near the zenith are of special interest.

Observers possessing suitable measuring devices determine the angular elevation from the horizon to the lower edge of each form whenever possible. Angular elevations to the top of isolated ray forms are also measured. To aid the individual observer in the measurement of angular elevations, a simple inclinometer has been designed. Though light enough to be held in the hand, this instrument can give measurements accurate to within 1°.

A program using a more complicated and more precise instrument, the alidade, has been designed for groups of observers who can work consecutively during a major portion of the night. Participants in this program report the same data as the individual observers, but confine their observations largely to the meridian. Measurements are plotted on a card designed to fit into a slot on the instrument.

Intensity: The intensity of an auroral display is indicated by writing standard letter symbols next to the auroral form on the reporting card. A weak, or faint, aurora is approximately equivalent in brightness to the milky way; auroras with the brightness of a moonlit cirrus cloud are considered medium. Bright auroras have about the intensity of moonlit cumulus clouds, and very bright displays are much brighter than this.

Motions: Auroras commonly display characteristic motions. Drift motions—slow, steady, east-west motions that appear to vary systematically during the night—are observed as slow changes in position of an entire form. Drift is not immediately apparent as the forms normally move only a few degrees per minute. On the reporting card, the drift is shown by a horizontal arrow pointing in the direction of movement.

The expansion of the entire auroral zone is evidenced by a slow southward motion of the whole aurora, in which the forms rise progressively higher above the northern horizon, sometimes approaching or even crossing the zenith. This expansion can be recognized by comparing an observation with one made 15 minutes earlier. In the declining phase, the auroral zone is contracting and the motion is to the north, or lower in the sky toward the northern horizon.

Colors: Auroras are often of such low intensity that colors are not apparent. If this is the case, or when the color is the usual yellowish-green, the observer makes no report on color. Other colors, usually red, blue, or violet-grey are rare—occurring only about $\frac{1}{20}$th as frequently as the yellow-green—but significant. These are reported. Red may appear extensively in a display, especially in low latitudes. (An aurora that occurred on February 10/11, 1958, and was seen as far south as Cuba, was reported by many observers as red in color.) The red color may appear at the lower borders of arcs or bands, at the tops of rays, or as diffuse clouds.

Optical devices: A number of simple optical aids are used by visual observers. Color filters help to distinguish auroral forms and colors as well as screening out moonlight and scattered city light. Still, time-lapse, and color photography are used by many observers to provide permanent visible records of auroral events. Pairs of photographs taken of the same aurora from different ground locations permit accurate height determinations.

Status of the Program

By January 1958 about 430 active observers were taking part in the visual auroral program. Approximately 130 US Weather Bureau stations, most of them reporting hourly, and 30 airline pilots are participating. The IGY Auroral Data Center is receiving about 5000 reporting cards per month from the Weather Bureau and roughly 6000 per month from volunteer observers. To date, more than 36,000 auroral reports and more than 350,000 reports of no aurora have reached the Data Center. More than 1200 cards were received on the aurora of February 10/11, 1958. This extensive aurora was, therefore, the world's most widely observed display up to that time.

Based largely on data received from participants in the visual observation program, synoptic maps are being prepared on a 15-minute basis for every aurora reported in the United States (see Fig. 6). The maps show the overhead location of the aurora and its shapes, intensity, changes, colors, and movement. Data accumulated during Special World Days and Special World Intervals are making it possible to construct similar maps of the distribution of

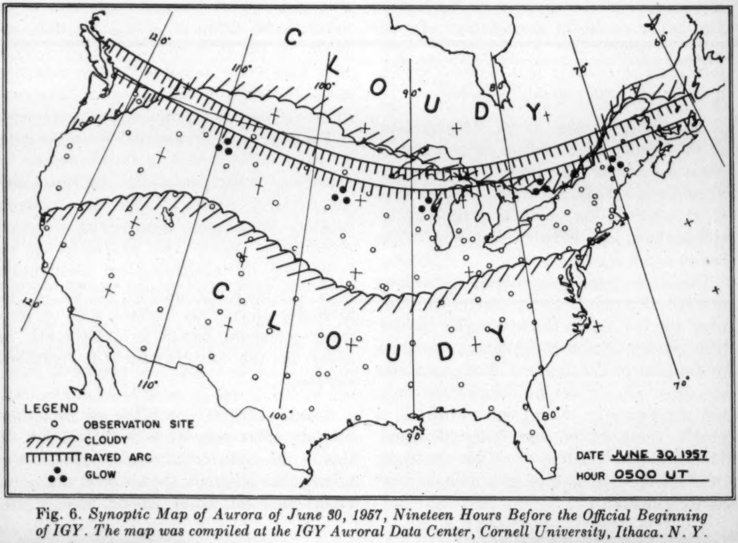


Fig. 6. *Synoptic Map of Aurora of June 30, 1957, Nineteen Hours Before the Official Beginning of IGY. The map was compiled at the IGY Auroral Data Center, Cornell University, Ithaca. N. Y.*

auroras over the entire globe for these periods of increased auroral activity. The maps prepared are microfilmed for international exchange.

Early Results: A number of interesting auroral features have already been reported in the Visual Observer Program. In large auroras, displacements of the coronas have been observed. Coronas, or radiant crowns, are formed when rays appear to converge (a perspective effect) as they approach the magnetic zenith—the position in the sky toward which the magnetic dip needle points.

Four months of Weather Bureau observations indicate that auroral motions are greatest at about midnight, and are predominantly from west to east.

The aurora is probably visible over the entire night side of the earth; continuous arcs have been observed for more than 2000 miles, and simultaneous auroral events have been observed from the English Channel to Ohio.

Arctic Sea-Ice Studies

This report is based on material supplied by Norbert Untersteiner, Department of Meteorology and Climatology, University of Washington.

As part of the IGY program for study of the earth's heat and water budget (described in *Bulletin No. 2, August 1957*) investigations of the physics of sea ice and the heat and moisture exchanges across the ice-atmosphere and ice-ocean interfaces are being conducted on IGY Drifting Station A in the Arctic Ocean ice pack (see Fig. 7).

The primary objective of these studies is to obtain data on the relative influence of the transfer of radiative heat and of latent heat on the mass budget of sea ice. (Radiative heat is heat released by emission or absorption of electromagnetic waves; latent heat is heat released by the change of state of water, i.e., melting, freezing, evaporation, condensation, etc.) Transfer of heat between the ocean and the atmosphere by conduction through the ice is also being studied. The investigations are scheduled to be carried out over a period of at least 12 months. This report covers some of the preliminary results of work done during the period June–September 1957.

The work is being carried out by the University of Washington Department of Meteorology and Climatology. IGY Drifting Station A, on a seven-foot-thick ice floe with an area of about four square miles, was established and is supported and maintained with the help of the US Air Force. It was first occupied on April 5, 1957; its position on April 24, 1958, was 84°N, 152°W, about 375 mi from the North Pole

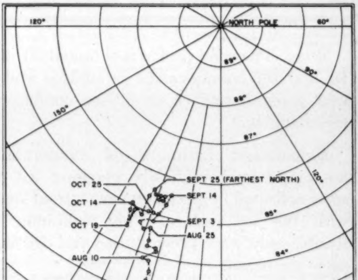


Fig. 7. *Movement of US-IGY Drifting Station A in Arctic Ocean, May 27–October 25, 1957.*

and 925 mi north of Barrow, Alaska. All equipment was installed on the drifting station by mid-June, well before the onset of melting.

Drifting stations are advantageous for studying the earth's thermal budget and other meteorological factors since they are distant from land masses and are surrounded by a uniform surface, conditions that make the data accumulated representative of a large area.

Techniques of Observation

Radiation: A radiometer is used to measure separately the total amounts of both incoming and reflected radiation; solarimeters measure the incoming and reflected short-wave radiation.

Temperature: Air temperatures are measured at 25, 50, and 100 cm above the ice by use of copper-constantan thermocouples. Thermocouples installed at three sites also measure temperatures at four levels in the ice. Ocean temperatures at a depth of three meters below the ice are obtained by use of additional thermocouples. A 16-point recorder is employed when continuous records are required.

Wind: The wind profile is obtained 20, 40, 80, and 160 cm above the ice surface whenever general weather or surface conditions are changing.

Evaporation: Estimates of evaporation are made by periodically weighing ice or snow collected in plexiglass pans buried level with the ice surface. This technique is feasible only when precipitation and drifting snow are absent.

Mass Budget Measurements: Direct evaluation of the change in total mass of the ice pack has been difficult. Measurement of ablation (loss of snow or ice, primarily by melting) at 16 localities appears to have established satisfactorily the loss of solid ice. But the initial amounts of snowfall and of melt beneath the cover of snow and slush could only be estimated. Too many observation sites would have been needed for an adequate measure owing to the collection of water in many depressions on the irregular surface of the floe, and to the extent of natural and artificial drainage.

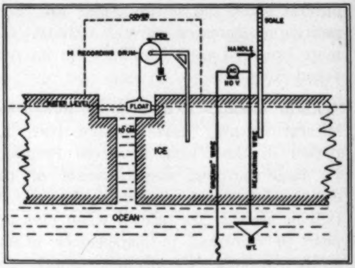


Fig. 8. *Water-Level Recorder (left) and Instrument for Measuring Accretion and Ablation at the Bottom of the Ice (right). The recorder utilizes a float placed in sea water which partially fills a pit; at the bottom of the pit a hole is drilled through the ice to the sea. A pen records water-level fluctuations on a drum.*

Mass changes at the ice bottom are measured by the other device. It consists of a measuring wire extended vertically through the ice; a cross bar is attached at the bottom. The wire, normally frozen into the ice, can be released by sending a current through a circuit completed by a second wire reaching the ocean. The measuring wire can then be pulled up until the cross bar touches the ice bottom. Readings are made on a scale fixed in the ice.

In anticipation of these difficulties, a water-level recorder was set up to determine relative height changes between the water surface and a fixed level in the ice (Fig. 8). This indicated how far the ice floe rose after natural and artificial drainage and how much lower in the sea it floated under a mantle of new snow. These records, however, do not distinguish mass changes at the surface from those at the bottom of the ice. Moreover, the instrument is only 1/9 as sensitive to ablation and accretion at the ice bottom as it is to these factors at the ice surface. In order to make the bottom measurements more accurately, another instrument was devised (also shown in Fig. 8). In addition, total thickness can be determined with greater ease and accuracy using this device than by drilling to the bottom of the floe.

Additional Measurements: Measurements are also made of the thickness and density of the ice, chlorine content (or salinity) of the sea water, and surface temperature (with thermocouples).

Accumulation and Ablation at the Surface of the Ice

An estimated 40 cm of snow, with a density of 0.3–0.4 gm/cm^3, accumulated during the winter and spring before melting began. Melting, which started in mid-June, was rapid owing to the low albedo (percentage of visible light reflected by a natural surface) of water and water-saturated snow. The snow cover had almost completely disappeared by July 8. Stakes were then emplaced for measurement of ice ablation, which averaged about one cm/day during the main ablation period, July 9–24.

Following the ablation period, a blanket of new snow began to develop, occasionally interrupted by brief melting periods. After August 8, however, accumulation increased steadily. The new snow cover reached a depth of approximately 20 cm by the end of September. Figure 9 summarizes the results of these accumulation-ablation observations during the summer of 1957 and Figure 10 portrays them diagrammatically.

During early July, the melt water ponded on the surface reached its greatest extent, covering approximately 30% of the total surface area. On July 3, when the water-level recorder was installed, the temperature of the central portion of the ice (at depths of 150–200 cm) was −3.5°C. Ice at these depths was essentially impermeable to melt water, and run-off over the edges of the floe was negligible. Therefore, virtually all melt water that had collected by early July still remained on the surface of the floe. By mid-August, holes had been melted through the ice, allowing the water to drain off and the floe to rise higher in the sea.

Water Level Records: As shown by water-

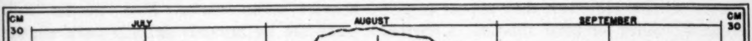


Fig. 9. *Graph of Mass Changes and Vertical Movement of the Ice Floe During the Summer of 1957.*

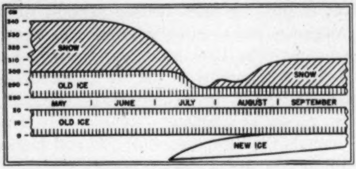


Fig. 10. *Schematic Diagram of Mass Changes, May–September 1957.*

level records, the ice floe rose a maximum of 29.6 cm from June through August 15, 1957. This is equivalent to a loss of 32.8 cm of ice. As determined by ablation measurements, on the other hand, the total ice loss, including melting of the spring accumulation of snow, was 26.5 cm. The difference of 6.3 cm may be accounted for by assuming a greater ablation in melt-water ponds, which covered 15–30% of the surface area for a three-week period. (The dashed line in Figure 9 indicates that ablation beneath 15 cm of water is approximately twice as great as that of bare ice.)

It is not possible to use the water-level records for ablation determinations over short periods. However, they appear to give reliable values for total ablation. A further practical characteristic of these records is the fact that they show runoff, or the amount of ice actually removed from the surface, rather than melting.

Stake Readings: For the period July 25–September 6, stake readings indicate a total accumulation of 3.4 cm of ice. The ice accumulation shown by the water-level recorder for the same period was 2.4 cm. Again the stake readings are considered less reliable as they represent level-ice conditions and do not account for the effects of the numerous hummocks or mounds. No appreciable accumulation was shown during this period by four stakes set on hummocks, which were about one meter high and 15 meters across.

Accretion and Ablation at the Bottom of the Ice:

On July 21, drilling revealed a newly-formed ice layer 1–3 cm thick beneath the pack ice. A layer of fresh water or slushy ice, with a temperature of 0°C and of varying thickness, separated it from the previous ice bottom. Further drilling showed that the distribution of this fresh-water layer was related to the topography of the underside of the pack ice. Pools formed under places where the ice was thin (about 250 cm) and were absent beneath hummocks and thick ice (greater than 300 cm).

Early in its development, a sample of this new ice was obtained with a coring auger. It was practically free of salt. At one locality, the layer had grown to a thickness of 20 cm by July 25. Here, the new ice was separated from the original ice bottom by 12 cm of fresh water. A constant temperature of −1.6°C was recorded in the ocean water beneath the new ice layer.

Manner of Formation of New Ice Layer: The layer of new ice appears to form as follows: Fresh surface melt water seeps through drain holes and pores in the pack ice, eventually accumulating at the ice bottom. There it floats on top of the cold, heavier ocean water. Fine, needle- and plate-like ice crystals develop between the fresh and salty water. These unattached crystals rise, gradually forming a loose, delicate fabric in the layer of fresh water, too tenuous to be felt when drilling. When these newly formed crystals can no longer rise, a solid layer begins to develop along the boundary between fresh and salt water, at the bottom of the network of fine crystals.

It was observed during August that this sub-layer of new ice, once formed, appeared to move upward while showing little increase in thickness. It seems unlikely that this rise was caused by buoyancy as it is assumed that the fine crystal network filling the fresh-water layer would be resistant to the buoyant force of ice forming along its lower margin. Probably, the rise of the top of the sub-layer actually results from freezing of the fresh-water layer, and the rise of its bottom surface represents melting of the fresh ice by the action of salty ocean water. The latter assumption is supported by the observation that the ice continued to thin even after the fresh-water layer above it had completely frozen. This bottom ablation may end when surface cooling penetrates to the bottom of the ice pack.

The formation of this sub-layer of 20 cm of fresh ice by July 25 indicates unexpectedly rapid freezing. The growth of the sub-layer with time can be expressed by the equation—

$$s = -1 + (4 + 17t)^{1/2},$$

in which s = thickness in cm, and t = time in days. Under the ideal conditions implied in the formula, the thickness of the ice layer would increase from 1 cm to about 23 cm in 20 days. This agrees well with the observed increase. However, the formula neglects the possible ablation of the bottom of the sub-layer owing to the action of salt water; hence, it tends to give a maximum thickness. Moreover, if accumulations of fresh water under the pack ice were initiated during an interval of rapid ice drift (from June 17 to July 17 the average drift of the floe was 8 km/day) and turbulent mixing, a fresh-ice layer might not form at all.

Mass Budget: The formation of this sub-layer of fresh ice may be of basic significance in the mass budget of the ice pack.

Studies up to the present lead to the assumption that throughout the Arctic Basin sufficient heat is supplied during part of the summer to melt the recent snow cover as well as a certain amount of solid, or "old," ice. The thickness of the pack ceases to change when the annual accretion at the bottom of the ice is equal to summer ablation. Much of this bottom accretion may consist of the fresh-water ice. This possibility will be investigated further when studies of the salinity of pack ice are carried out.

Owing to continuing accretion at the bottom of ice of stationary thickness, it is assumed that there is an upward movement of mass within the ice pack. It should be expected, therefore, that on a very old, unbroken floe, the oldest ice lies immediately beneath the surface layer of new spring ice.

Thermal Budget

Data evaluation thus far permits only a few preliminary statements about the summer thermal budget. It is apparent that long-wave radiation is of great importance in surface melting. Throughout the observation period, melting occurred primarily when the sky was overcast and atmospheric radiation was strong. Freezing at the surface often accompanied short breaks in the overcast. Balloon soundings revealed frequent inversions in atmospheric temperatures, with comparatively high ceiling temperatures.

During melting, the pack-ice surface disintegrates into a loose layer of coarse, granular ice, which has a high albedo—higher than that of clean glacier ice. This may result from a difference in crystal structure and the penetration of radiation into the pack ice.

Temperature gradients in the layer of air just above the ice surface are usually very small or virtually lacking, according to measurements made 25, 50, and 100 cm above the ice. The humidity regime in this layer appears to be similar to the temperature regime. Direct measurements, made by weighing snow-filled pans, indicate that maximum evaporation occurred on June 29. A heat loss of 30 cal/cm^2 over a period of 12 hours was measured on this date. The maximum condensation, involving a heat gain of 16 cal/cm^2 in 12 hours, took place on September 14. Average heat gain is normally only several cal/day.

On the basis of observations made during the June–September 1957 period, it is expected that further data will show radiative heat to be the most important element in the summer thermal budget and in melting. The transfer of both sensible heat (heat released by turbulence or molecular conduction) and latent heat appear to be less significant.

Optical Tracking of Earth Satellites

This report was compiled from materials furnished by the Smithsonian Institution Astrophysical Observatory, Cambridge, Massachusetts, which directs the US-IGY optical tracking program. Reports on other satellite tracking programs may be found in *Bulletins 6* and *10* (volunteer visual and radio tracking), *2* (prime radio system), and *9* (volunteer photographic tracking).

Of the several satellite tracking programs designed for the IGY—radio, visual, and optical—it is the optical which is intended to obtain orbital and positional data of maximum precision. Once a satellite is located, or "acquired," by other means, and its orbit computed, precision optical tracking is accomplished by large tracking cameras. These tracking cameras cannot be used for acquisition because of their relatively restricted field. (The path of the satellite must first be known to within 3° of arc in order to aim the cameras.)

Baker-Nunn Tracking Camera

The precision camera designed for the US-IGY satellite tracking program is the Baker-Nunn camera, a modification of the Schmidt meteor camera.

Under optimum conditions, the Baker-Nunn tracking cameras will measure a satellite's position to an accuracy of two seconds of arc and $1/1000$ second in time. The camera is named for James G. Baker, who designed the optical system, and Joseph Nunn who designed the mounting, tube, drives, and other mechanical parts.

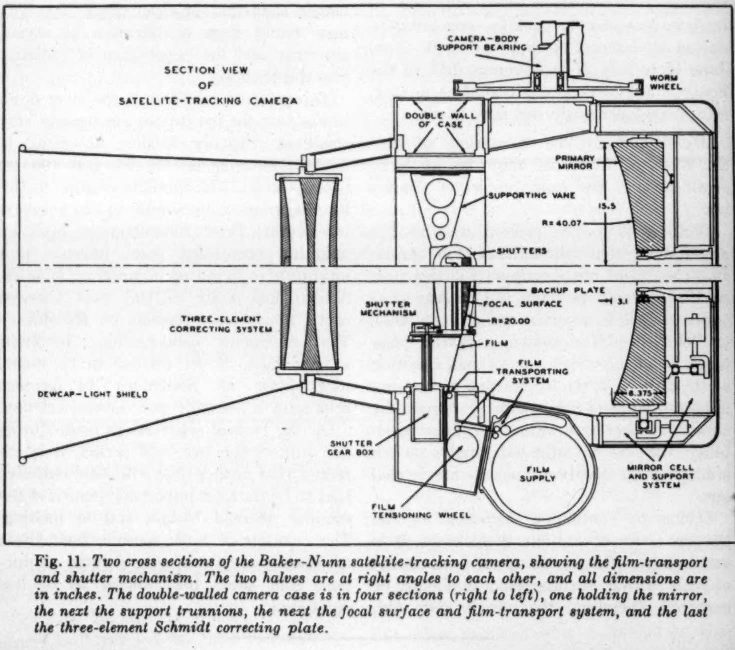

SECTION VIEW
OF
SATELLITE-TRACKING CAMERA
CAMERA-BODY SUPPORT BEARING
WORM WHEEL
DOUBLE WALL OF CASE
PRIMARY MIRROR
SUPPORTING VANE
15.5
R=40.07
SHUTTERS
BACKUP PLATE
3.1
SHUTTER MECHANISM
FOCAL SURFACE
R=20.00
THREE-ELEMENT CORRECTING SYSTEM
FILM
FILM TRANSPORTING SYSTEM
DEWCAP-LIGHT SHIELD
6.375
SHUTTER GEAR BOX
FILM SUPPLY
MIRROR CELL AND SUPPORT SYSTEM
FILM TENSIONING WHEEL

Fig. 11. *Two cross sections of the Baker-Nunn satellite-tracking camera, showing the film-transport and shutter mechanism. The two halves are at right angles to each other, and all dimensions are in inches. The double-walled camera case is in four sections (right to left), one holding the mirror, the next the support trunnions, the next the focal surface and film-transport system, and the last the three-element Schmidt correcting plate.*

Optical System: This camera utilizes a Schmidt optical system with a new type of correcting system. It has a focal length of 20 inches, an aperture of 20 inches (thus giving a focal ratio of f 1.0), and a field of 5° x 30°. The camera uses 55-mm Cinemascope film. Each photograph is about one foot long. The complete optical system is shown in Figure 11.

Camera Mounting: Use of a three-axis mounting permits the camera to track in any direction across the sky. For tracking, two axes are clamped in fixed positions and the camera body is rotated about the third axis by an electric drive.

TABLE 1

Angular Velocity (min of arc/sec)	*Limiting Magnitude*	
	Stationary	*Tracking*
87.8	5.8	10.8
42.1	6.6	11.6
19.4	7.4	12.4
8.9	8.3	13.3
0.25*	12.2	17.2

* This is the sidereal rate at the celestial equator. In this table, it is assumed that 80% of the light falls within a 30-micron circle. The satellite-tracking cameras in the US-IGY program exceed this efficiency.

Position Measurements: Traditional astronomical methods of measuring image positions relative to star images on the film are necessary in order to achieve the precision of two seconds of arc. When the satellite is tracked at maximum orbital velocity, the stars will trail and only those brighter than approximately 5.8 magnitude will be recorded. Usually, only two or three stars of this brightness can be expected to fall in the 5° x 30° field. If measurements must be made from the star image to the satellite image across several inches of film, stretching of the film and distortion of the emulsion will introduce greater errors than can be tolerated.

In order to avoid long measurements, the camera tracks alternately at the satellite rate and at the rate of sidereal (star) motion parallel to the satellite orbit. In this way exposures of both the satellite and the background of faint stars can be made on a single film. The satellite position is then measured relative to nearby star images. Satellite motion between the two exposures is compensated for by measuring the distance between the "star-exposure" images of the bright stars and the "satellite-exposure" images of these same stars. This distance will never exceed one inch, and the amount of film stretching over this distance will not introduce excessive error in the measurements.

A time reference is provided by using a rotating barrel-type shutter which causes sharp breaks in the trails of both the satellite and the bright stars. This shutter is shown in the upper part of Figure 11 as a cylinder enclosing the film back-up plate. Outside the barrel shutter is a "clamshell" shutter which opens and shuts to begin and end each exposure.

Tracking Cycle: For each film exposed, the camera automatically runs through a basic cycle that can be set at 2, 4, 8, 16, or 32 seconds. During this cycle, the tracking rate varies from sidereal to satellite and back again.

To begin the cycle, the clamshell shutter snaps open for an interval of 0.1 cycle, during which the exposure is chopped into four segments by the continuously rotating barrel shutter. At the instant of some one chop, a stroboscopic flash illuminates the time-display unit attached to the camera and the time is recorded photographically. After the clamshell closes, the tracking rate decelerates to the sidereal rate and the clamshell opens again for 0.1 cycle. This star exposure is likewise chopped into four segments, but the time is not recorded. After the shutter closes again, the film is automatically changed and the cycle repeats.

Effective Exposure: The setting of the mean tracking rate is continuously variable and in practice can be adjusted so that the camera tracks the satellite with an error of one percent or less. Tracking increases the effective exposure time by a factor of 100 over that possible if the camera remains stationary. This increase in effective expo-

TABLE 2

Station	Longitude	Latitude
Organ, New Mexico, U.S.A.	106°53′W	32°6′N
Olifantsfontein, South Africa	28°15′E	25°58′S
Woomera, Australia	136°48′E	31°08′S
Cadiz, Spain (Naval Obs., San Fernando)	6°12′W	36°28′N
Tokyo, Japan (Tokyo Astron. Obs., Mitaka)	139°33′E	35°40′N
Naini Tal, India (St. Uttar Pradesh State Obs.)	79°27′E	29°24′N
Arequipa, Peru	71°31′W	16°22′S
Shiraz, Iran	52°33′E	29°36′N
Curacao, N.W.I. (St. Barbara, Willemstad)	68°52′W	12°06′N
Hobe Sound, Florida, U.S.A. (Jonathan Dickinson State Park)	80°7′W	27°01′N
Villa Dolores, Argentina	65°6′W	31°57′S
Haleakala, Maui, Hawaii	156°16′W	20°43′N

sure means that objects five magnitudes greater than otherwise possible can be photographed. Table 1 shows the limiting magnitudes for different tracking rates.

Time Measurement: The greatest possible angular velocity for a satellite in orbit is 5300 seconds of arc per second of time. Thus, a measuring accuracy of two seconds of arc in the direction of motion in this extreme case requires a determination of time to $1/2500$ second. Such accuracy cannot be maintained under field conditions but the time unit used on the camera does allow time measurements to $1/1000$ second.

The primary component of the time unit is a crystal clock. Added to this are a radio receiver for WWV time signals, a system of time presentation readable to $1/10.000$ second, and a "slave" clock that will duplicate the time presentation within the body of the telescope, where it can be photographed during each operating cycle of the camera.

The time presentation includes a rotating dial that indicates time to $1/100$ second, and an amplitude-modulated circular-sweep oscilloscope which can be read to $1/10.000$ second. This displays the output of the clock and compares it with the signal received from WWV. If daily comparisons with WWV are made, the error of this time system is held to $1/1000$ second.

Tracking Stations: The first Baker-Nunn Camera was installed at Organ, New Mexico, on November 15, 1957. Table 2 shows the location of all 12 precision photographic tracking stations of the US-IGY program.

Of the nine stations established outside United States territory, six are operated in cooperation with the IGY committee and other scientific organizations of the nations concerned. Australia, Japan, and India have assumed complete operating responsibility for their stations. Other countries have provided varying degrees of support in the form of personnel, sites, facilities, operating expenses, and communications. In addition to this extensive international cooperation, the optical tracking program has received valuable logistic and operational support from the US Air Force, Army, and Navy.

The locations were selected to give maximum coverage on satellites with orbits inclined at 35°–40° to the equator.

Through a special communications network, the Smithsonian Astrophysical Observatory provides each station with information on camera settings for each visible pass of each satellite. Each station develops the films as soon as possible, makes preliminary reductions of position data, and sends the information to the Astrophysical Observatory through the same communications net. The negatives are forwarded later for detailed analysis.

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Gravity Measurements in the Queen Elizabeth Islands of Arctic Canada

A. M. BANCROFT

Abstract—Principal facts are presented for five gravity stations in the Canadian Arctic north of latitude 74° N. The accuracy of the measurements is discussed, and station descriptions are included so that the gravity sites may be used as bases for further work in the Queen Elizabeth Islands.

Introduction—The extension of our knowledge of the Earth's gravitational field to more remote regions is essential if the world-wide geodetic applications of gravity are to be utilized. The establishment of five permanent weather reporting stations in the Queen Elizabeth Islands since 1946 [*Rae*, 1954] has made access to this region possible (Fig. 1). The annual resupply of the four northern stations from Resolute by the Air Transport Command of the RCAF has enabled the Dominion Observatory to employ gravimeters to make measurements at all five stations.

The area is interesting historically in that the first measurement of gravity in Canada was made at Winter Harbour, Melville Island in 1820, during the Parry Expedition of 1819–20 [*Sabine*, 1821]. Pendulum measurements were also made at Fort Conger in northern Ellesmere Island during the ill-fated Greely expedition [*Greely*, 1888].

Previous work—Apart from Sabine's work, the first measurement of gravity in the Queen Elizabeth Islands was made in 1948, when graduate students of the University of Toronto established a pendulum gravity station at Resolute [*Beer*, 1950]. This result, coupled with previously established pendulum stations at Churchill and Ottawa [*Innes*, 1948] made it possible to calibrate a geodetic-type Worden gravimeter (No. 44) by flying between Dorval Airport (Montreal), Churchill, and Resolute Bay. This was done in 1951 by P. M. Millman, in 1952 by J. A. Robinson, and in 1953 by M. J. S. Innes and J. A. Robinson. The adjustment of the results of these calibrations gave a value at Churchill Airport of 981.7668 gal (Table 1). This figure was in satisfactory agreement with a value of 981.7670 found by an overall adjustment of the pendulum station values of gravity in northern Ontario, Manitoba, and Saskatchewan [*Innes* and *Thompson*, 1953]. The mean value of gravity which is adopted in this report is therefore $g = 981.7669$ gal at the Churchill Airport site.

The mean gravimeter value obtained with the Worden instrument at Resolute Airport (Table 1) will be referred to later in this report.

Gravimeter observations at the other weather stations have been made by J. A. Robinson in 1952 and by United States observers [*Woollard, Black*, and *Bonini*, 1954]. As there is some uncertainty about station locations the results have not been compared with the 1957 observations presented here.

The observations—The gravimeter used was a North American instrument (No. 137) with a range of 1200 mgal. This instrument has considerably greater accuracy than Worden meter 44 when measuring gravity differences greater than about 100 mgal. (The errors in the Worden instrument are dominated by temperature effects and by uncertainties in the calibration of the large dial). With the present instrument a special light-weight battery was used, composed of four silver-zinc cells strapped around the carrying frame (Fig. 2). The whole was arranged to be carried on the observer's chest rather than his back. The battery was successfully used for periods of up to 30 hr before recharging.

An additional refinement has been incorporated into this gravimeter by R. L. G. Gilbert of the Dominion Observatory in an unpublished study undertaken in 1957. This consists of a sapphire ball, 1/16 inch in diameter, which can be lowered onto the beam of the instrument; the change in reading (about 350 divisions) is determined. This enables the calibration constant of the instrument

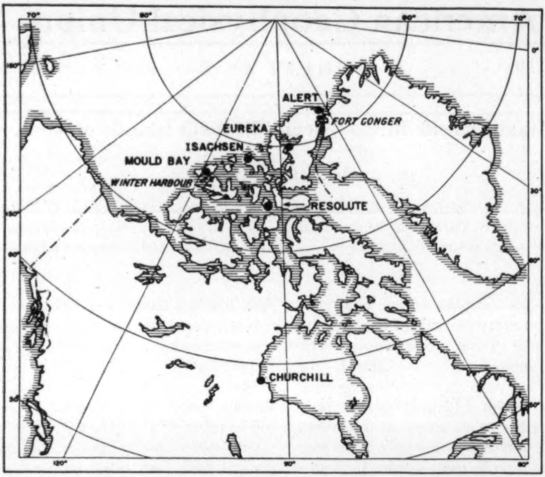

FIG. 1 - Outline map showing location of gravity stations

TABLE 1 - *Values of gravity obtained at Churchill and Resolute from least-squares analyses of observations with Worden Gravimeter 44*[a]

Item	Churchill	Resolute
Pendulum values	981.7657	982.8641
Gravimeter values (1951)	981.7668	982.8635
" " (1952)	981.7665	982.8637
" " (1953)	981.7673	982.8633
Mean gravimeter values	981.7668	982.8635

[a] All values are referred to the stations shown in Fig. 3.

to be checked for changes with time, latitude, or the position of the reading dial.

The instrument was taken twice from Churchill to Resolute, readings being taken in every case immediately before departure and upon arrival; this operation was completed in 31 hr. Two round trips were made from Resolute to each of the other four weather stations, the flights to Mould Bay and Isachsen being made in quick succession, so that a satisfactory correction for instrumental drift could be made. The two flights to each of the other two stations were made on separate days so that the results do not have quite the same strength. However, all eight sorties from Resolute were completed in nine days so that in view of the nature of the operation it is felt that the time between repeat readings was kept satisfactorily low.

FIG. 2 - Reading the gravimeter at Resolute; the carrying frame with the silver-zinc cells attached is directly in front of the instrument

Care was taken in the descriptions of the sites of the gravimeter bases (Figs. 3 and 4). The gravity stations at Churchill and Resolute are the same as those used by previous Dominion Observatory parties. At the other four weather stations the

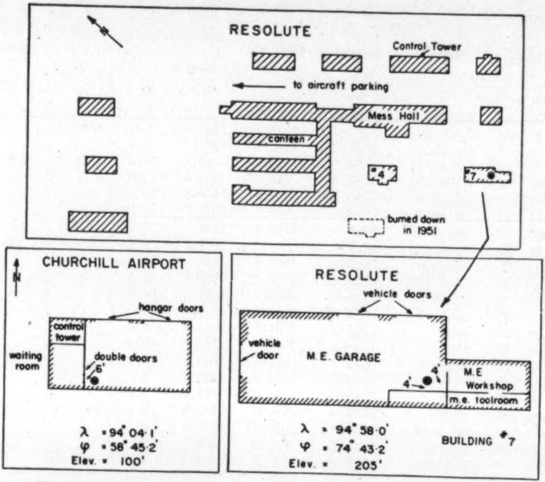
RESOLUTE
Control Tower
to aircraft parking
Mess Hall
canteen
4
7
burned down in 1951
CHURCHILL AIRPORT
N
hangar doors
control tower
waiting room
double doors
6'
λ = 94° 04·1'
φ = 58° 45·2'
Elev. = 100'
RESOLUTE
vehicle doors
vehicle door
M.E. GARAGE
4'
4'
M.E Workshop
m.e. toolroom
λ = 94° 58·0'
φ = 74° 43·2'
Elev. = 205'
BUILDING # 7

FIG. 3 – Location sketches for gravity stations at Churchill and Resolute

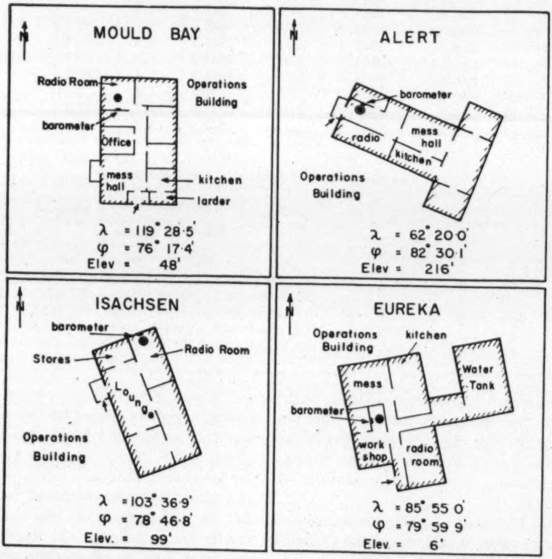
MOULD BAY
N
Radio Room
Operations Building
barometer
Office
mess hall
kitchen
larder
λ = 119° 28·5'
φ = 76° 17·4'
Elev = 48'
ALERT
N
barometer
radio
mess hall
kitchen
Operations Building
λ = 62° 20·0'
φ = 82° 30·1'
Elev = 216'
ISACHSEN
N
barometer
Stores
Radio Room
Lounge
Operations Building
λ = 103° 36·9'
φ = 78° 46·8'
Elev. = 99'
EUREKA
N
Operations Building
kitchen
Water Tank
mess
barometer
work shop
radio room
λ = 85° 55·0'
φ = 79° 59·9'
Elev = 6'

FIG. 4 – Location sketches for stations at Mould Bay, Alert, Isachsen, and Eureka

TABLE 2 – *Reduction of observations*

Date	Time (EST)		Station	Reading	Reading corrected for diurnal change	After removal of ground drift			Mean ΔR	Δg
						Reading	Δt	ΔR		
1957	h	m		div	div	div	hr	div	div	gal
Mar 27	07	33	Churchill	55.1	55.1	55.1	0	...	...	...
	13	58	Resolute	4637.2	4637.2	4637.2	6.4	4581.3	...	...
	14	02	Resolute	4637.2	4637.2	4637.2	6.4	...	...	...
	20	38	Churchill	56.6	56.8	56.8	13.0	4581.3	4581.3	1.0962
Mar 28	07	30	Churchill	58.6	58.6	56.8	13.0	...	...	...
	14	16	Resolute	4640.7	4640.8	4639.0	19.8	...	...	...
Apr 4	14	21	Resolute	1618.6	1618.8	1618.8	0	...	...	...
	18	25	Mould Bay	1915.9	1916.1	1916.1	4.1	297.1	...	...
	21	25	Resolute	1619.0	1619.1	1619.1	7.1	297.1	296.9	0.0710
Apr 5	05	05	Resolute	1618.8	1618.7	1619.1	7.1	...	...	...
	09	25	Mould Bay	1916.1	1916.1	1916.4	11.4	296.5	...	...
	12	50	Resolute	1620.9	1620.9	1621.3	14.8	...	...	...
Apr 6	17	28	Resolute	1649.2	1649.4	1649.4	0	0	...	...
Apr 7	03	20	Alert	2781.5	2781.5	2781.5	9.9	1132.1	...	...
	04	58	Alert	2780.6	2780.6	2781.5	9.9	...	...	...
	14	15	Resolute	1648.3	1648.4	1649.3	19.2	...	1132.5	0.2710
Apr 9	22	58	Resolute	1649.8	1649.9	1649.9	0	0	...	...
Apr 10	08	40	Alert	2783.0	2783.0	2783.0	9.7	...	...	...
	09	55	Alert	2781.8	2781.8	2783.0	9.7	1132.9	...	...
Apr 11	13	25	Resolute	1649.4	1649.5	1650.7	37.2	...	...	...
Apr 7	14	50	Resolute	1648.5	1648.6	1648.6	0	...	...	...
	18	15	Isachsen	2458.3	2458.3	2458.3	3.4	809.9	...	...
	20	50	Resolute	1648.0	1648.2	1648.2	6.0	809.7	...	...
Apr 8	00	42	Resolute	1649.0	1649.0	1648.2	6.0	...	809.6	0.1937
	04	50	Isachsen	2458.1	3458.1	2457.3	10.1	809.3	...	...
	07	12	Resolute	1648.8	1648.7	1647.9	12.5	...	...	...
Apr 11	14	10	Resolute	1649.8	1649.9	1648.9	0	0	...	...
	18	00	Eureka	2345.1	2345.1	2345.1	3.8	693.3	...	...
	18	15	Eureka	2344.5	2344.5	2345.1	3.8	...	691.3	0.1654
	21	50	Resolute	1653.6	1653.6	1654.2	7.4	690.2	...	...
Apr 13	08	08	Resolute	1655.6	1655.6	1654.2	7.4	...	...	...
	12	24	Eureka	2344.9	2345.0	2343.6	11.7	690.4	...	...
	15	58	Resolute	1653.8	1653.9	1652.5	15.3	...	...	...

TABLE 3 – *Principal facts for gravity stations*

Station	Longitude		Latitude		Elevation	Theoretical gravity	Computed gravity		Observed gravity	Gravity anomalies	
							Free-air	Bouguer		Free-air	Bouguer
	°	′	°	′	ft	gal	gal	gal	gal	gal	gal
Resolute	94	58.0	74	43.2	205	982.86059	982.84131	982.84829	982.8631	0.0218	0.0148
Mould Bay	119	28.5	76	17.4	48	982.92954	982.92503	982.92666	982.9341	0.0091	0.0074
Isachsen	103	36.9	78	46.8	99	983.02464	983.01533	983.01870	983.0568	0.0415	0.0381
Eureka	85	55.0	79	59.9	6	983.06462	983.06406	983.06426	983.0285	−0.0356	−0.0358
Alert	62	20.0	82	30.1	216	983.13285	983.11253	983.11989	983.1341	0.0216	0.0142

gravimeter was read on the floor adjacent to the barometer in the operations building. This was done because in each case the elevation of the barometer was known, and the chances are improved for recovery of the gravity stations by future observers.

The results—The values of gravity presented here are based on the adopted value of *g* at the Churchill Airport station of 981.7669 gal.

The gravimeter readings were first corrected for diurnal variations caused by the changing attractions of the Sun and Moon, using the tables of *Goguel* [1956]. Next, the readings were corrected for instrument drift and values of the difference in reading (ΔR) were computed. Lastly, the mean ΔR for each connection was calculated. These results are summarized in Table 2. They are presented here to allow their reliability to be independently assessed, and because when improved pendulum observations are available, the data will be needed in a final adjustment.

The conversion of the ΔR values to gravity differences is based upon a calibration of the instrument along the Ottawa – Washington base line [*Saxov*, 1956]. In June 1957, the calibration constant obtained was $K_{137} = 0.23914$ mgal/div.

Tests made by weighing the sapphire ball in May and in June indicated that the May 1957 value was the better value to adopt for the period of the survey. This was $K_{137} = 0.23927$ mgal/div.

Additional tests carried out with the sapphire ball at Churchill and Resolute gave secondary scale constants: $K_{137} = 0.2392$ mgal/div for Churchill – Resolute; and $K_{137} = 0.2390$ mgal/div north of Resolute.

The decision not to accept the indicated change of scale constant with latitude was largely based upon the uncertainty of the ball tests at Resolute. The graph of the effect of the ball plotted against dial position does not have the same form as at other locations, which makes the reliability of the Resolute measurements suspect. Gravity values have therefore been computed using the calibration constant $K_{137} = 0.23927$ mgal/div throughout. The observed gravity differences are added to the adopted value at Churchill to obtain the observed value of gravity at each of the other stations.

The final results are presented in Table 3. The computed values of gravity are calculated according to the International Gravity Formula, first at sea level and then at the elevation of the station for both the free-air and Bouguer reductions. In the free-air reduction no account is taken of the material between station elevation and sea level, while allowance is made in the Bouguer reduction assuming a rock density of 2.67 gm/cc. The differences between the observed and computed values give the free-air and Bouguer anomalies listed in the last two columns.

It is interesting to note that the value of gravity for Resolute presented in Table 3 is only 0.4 mgal less than the previously adopted value based upon a combined analysis of pendulum measurements and the readings of the Worden instrument 44 (Table 1). In view of the uncertainty of our knowledge of the large dial/small dial ratio of the Worden instrument no attempt has been made to combine the results.

An estimate of errors can be made only in the broadest terms. With the exception of the Resolute – Eureka connection, the scatter in the individual determinations of ΔR is less than one division, so that the error due to this source is not more than 0.2 mgal. On the other hand, systematic errors due to the uncertainty of calibration may be considerable. An error of one part in 1000 in the scale constant determination, which is not inconceivable, would result in an error of more than 1 mgal in the Churchill – Resolute connection alone. Hence, while the values of gravity are probably consistent among themselves to better than 0.2 mgal, they may be too high or low relative to Ottawa by about one mgal. However, until such time as improved pendulum determinations can be made, the values published here should prove quite adequate for both geodetic purposes and as base stations for further observations in the Queen Elizabeth Islands.

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Planetary Waves and Jet Streams in the Atmosphere*

S.-K. KAO

Abstract—A systematic analysis of planetary waves in a zonal current with jet stream, linear velocity-shear, and uniform angular velocity shows that (1) the phase velocity of the planetary waves in a zonal current with jet stream increases or decreases depends respectively on the narrowing or broadening of the jet stream, (2) the increase or decrease of the dimension of the planetary waves follows respectively the broadening or narrowing of the width of the jet stream, (3) the major effect of a linear velocity-shear in a zonal current is to damp out waves in the current, (4) the streamline pattern in a zonal current on a spherical Earth with uniform angular velocity exhibits major characteristic features in the atmosphere such as subtropical highs, jet stream, westerly waves, high latitude lows and polar easterlies, and (5) the effect of viscosity is to damp out all waves in the current.

Introduction—The discovery of planetary waves in the atmosphere may be considered as one of the important discoveries in the modern history of meteorology. The reason for its importance lies in the fact that planetary waves are closely coupled with weather systems and are semi-permanent, a characteristic which makes it easy to be predicted. The development of planetary wave stems from the principle of the conservation of absolute vorticity. Applying this principle to the study of atmospheric motion *Rossby* and collaborators [1939] obtained a wave solution on an Earth whose variation of Coriolis parameter with latitude is constant. Since then planetary-wave solutions of the vorticity equation for an inviscid fluid have been investigated by *Haurwitz* [1940 ab], *Ertel* [1943], *Craig* [1945], *Rombakis* [1948], *Höiland* [1951], and *Long* [1952], and for a viscous fluid by *Kao* [1954, 1955]. In recent years, synoptic analysis shows that the field of motion in the middle and upper troposphere is characterized by the presence of jet streams, planetary waves, and cyclonic and anticyclonic cells. Although it can be shown that solutions of vorticity equation permit the inclusion of these characteristic features of flow pattern in the atmosphere, the interaction between jet streams and planetary waves has not been studied. The objective of this note is to give a systematic account of the motion of planetary waves in a zonal current with jet streams, linear velocity-shear, and with uniform angular velocity.

Planetary wave motion in a zonal current with jet streams—If the vertical velocity is neglected and zero horizontal divergence is assumed, the vorticity equation of an autobarotropic atmosphere is

$$\left(\frac{\partial}{\partial t} - \frac{\partial \psi}{\partial y}\frac{\partial}{\partial x} + \frac{\partial \psi}{\partial x}\frac{\partial}{\partial y} - \nu\nabla^2\right)\nabla^2\psi + \beta\frac{\partial \psi}{\partial x} = 0 \quad (1)$$

where x and y are the Cartesian coordinates, positive toward the east and north respectively; ψ is the stream function, ν the coefficient of kinematic viscosity; ∇^2 is two dimensional Laplacian; $\beta = 2\Omega a^{-1} \cos \psi$ where Ω is the angular velocity of the Earth, a is the radius of the Earth, and φ is the latitude.

It can be shown that the following stream function

$$\psi = -U(t)y + \left\{A \sin\frac{2\pi}{D} y + B \sin\frac{2\pi}{L} \cdot \left[x - \int c(t)\,dt\right] \sin\frac{2\pi}{l} y\right\} e^{-\nu\frac{4\pi^2}{D^2}t} \quad (2)$$

satisfies the vorticity equation (1), provided that

$$1/D^2 = 1/L^2 + 1/l^2 \quad (3)$$

and

$$c(t) = U(t) - \beta D^2/4\pi^2 \quad (4)$$

where D is twice the width of the jet stream; L and l are respectively the wave length and twice the lateral extent of the planetary waves; $c(t)$ is the phase velocity of the wave; $U(t)$ is uniform part of the zonal velocity; A and B are respectively the amplitude of the jet stream and the planetary waves.

Partial differentiation of (2) with respect to $-y$ gives zonal component of the velocity,

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* In memoriam of Dr. Carl-Gustaf Rossby. Contribution from Meteorology Department, University of California at Los Angeles, No. 35.

$$u = U(t) - 2\pi\left\{\frac{A}{D}\cos\frac{2\pi}{D}y + \frac{B}{l}\sin\frac{2\pi}{L}\right.$$

$$\left.\cdot\left[x - \int c(t)\,dt\right]\cos\frac{2\pi}{l}y\right\}e^{-\nu\frac{4\pi^2}{D^2}t} \qquad (5)$$

It is to be noted that stream function (2) contains the following characteristic features of the field of motion in the atmosphere: (1) one or several jet streams with width $\frac{1}{2}D$; (2) a zonal current of uniform velocity $U(t)$ which is an arbitrary function of time; (3) planetary wave of finite amplitude with wave length L, and lateral extent $\frac{1}{2}l$; (4) cyclonic and anticyclonic cells.

A schematic diagram showing the distribution of streamlines of planetary waves, cyclonic and anticyclonic cells in relation to a jet stream is shown in Figure 1. Notice that on one side of the jet stream is a row of cyclonic cells, on another side a row of anticyclonic cells which, to some extent, resembles the flow pattern in the upper level.

Some interesting information may be obtained from relationships (3) and (4). It is seen from (3) that

$$D < L, l$$

which means that the width of jet stream is always smaller than half the wave length and the lateral extent of the planetary waves. Eq. (2) represents the quasi-stationary solution in which D, l, L are constants, and cannot be applied to transient situations. However, if one applies it to the quasi-stationary situations before and after a period of transition, one may infer from (3) that the increase or decrease of the dimension (lL) of the planetary waves follows respectively the broadening or narrowing of the width of the jet stream and vice versa. It is seen from (4) that the increase or decrease of the phase velocity of the planetary wave in a zonal current with jet stream depends respectively on the increase or decrease of the mean velocity of the zonal current, and depends respectively on the narrowing or broadening of the jet stream. It is worth noticing that the phase velocity of the planetary is independent of the intensity of the jet stream and the effect of friction is to damp out all waves in the current.

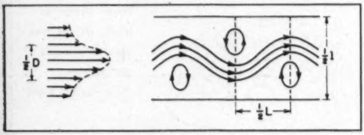

FIG. 1 – Stream-line pattern in a zonal current with jet stream

Planetary-wave motion in a zonal current with linear velocity-shear—For a rotating Couette flow with velocity shear S with respect to y, it can be shown that stream function

$$\psi = -U(t)y - \tfrac{1}{2}Sy^2 - \frac{AL^2}{4\pi^2[1 + (St + \xi)^2]}$$

$$\exp\left\{-\nu\frac{4\pi^2}{D^2}[(1 + \xi^2)t + S\xi t^2 + \tfrac{1}{3}S^2t^3]\right\}$$

$$\times \sin\frac{2\pi}{L}\left\{x - \int c(t)\,dt - Syt\right.$$

$$\left. + \frac{\beta L^2}{4\pi^2 S}[\tan^{-1}(St + \xi) - \tan^{-1}\xi] - \xi y - \delta\right\} \qquad (6)$$

satisfies vorticity equation (1). Here ξ^{-1} is the initial slope of the trough and ridge lines of the waves; δ is a constant to be determined by the initial condition. The first term of the right hand side of (6) gives the velocity of the Couette flow with lateral velocity-shear S; the last term gives a sinusoidal wave with an amplitude which varies with time; $(St + \xi)$ is the reciprocal of the slope of the trough and ridge lines with respect to y.

Note that no stationary or quasi-stationary waves are possible to occur in a zonal current with linear velocity shear, since waves in such a system move with a speed

$$c(t) = U(t) + Sy - \frac{\beta L^2}{4\pi^2[1 + (St + \xi)^2]} \qquad (7)$$

which depends not only on the velocity of the Couette flow, wave length, latitude, but also on the instantaneous slope of the trough and ridge lines of the waves. It is readily seen that for waves in an inviscid zonal current with uniform velocity, frequency equation (7) reduces to that of Rossby's wave [*Rossby* and collaborators, 1939]

$$c = U - \beta L^2/4\pi^2$$

Inspection of (6) reveals that the wave velocity and the slope of the trough and ridge lines vary with time. These are two characteristic features of wave motions in a zonal current with a linear velocity shear, whereas there is no change in the wave velocity and the inclination of trough and ridge lines in a zonal current with uniform velocity.

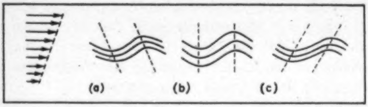

FIG. 2 – Stream-line pattern at different instances in a zonal current with linear velocity-shear

It is readily seen from (6) that waves will eventually disappear in a zonal current with linear velocity shear regardless whether the fluid is viscous or not. However, under certain conditions waves may be amplified within a certain time interval. Waves may be damped, unchanged, or amplified depending respectively on

$$S(St + \xi) + \nu 2\pi^2 L^{-2}[1 + (St + \xi)^2]^2 \gtreqless 0 \qquad (8)$$

For the case that the fluid is inviscid only the term $S(St + \xi)$ remains in (8). Waves will be amplified when the slope of the trough and ridge lines is in the opposite sign to the lateral velocity shear of the zonal current, that is, if $S\,\xi < 0$ and when $t < -S^{-1}\xi$ as shown in Figure 2a. Wave amplitude reaches its maximum when the trough and ridge lines are perpendicular to the zonal current ($t = -S^{-1}\xi$) as shown in Figure 2b, and drops when their slope is of the same sign as the lateral velocity shear as shown in Figure 2c. It is interesting to note that for the inviscid case maximum wave amplitude occurs when the extreme wave velocity is reached. Since the viscosity term in (8) is always positive, viscosity tends to suppress the amplification effect and bring the maximum wave amplitude to an earlier moment than in the case of an inviscid fluid.

Planetary-wave motion in a zonal current on a spherical earth with uniform angular velocity— In order to examine the effect of the curvature of a spherical Earth's surface on the motion of planetary waves let us consider spherical-surface flow of an incompressible viscous fluid with zero velocity divergence. For this case the vorticity equation and equation of continuity are respectively

$$\frac{\partial}{\partial t}\Delta\psi + \frac{1}{a^2 \sin\theta}\left(\frac{\partial\psi}{\partial\theta}\frac{\partial}{\partial\lambda} - \frac{\partial\psi}{\partial\lambda}\frac{\partial}{\partial\theta}\right) \cdot (\Delta\psi + 2\Omega a^2 \cos\theta) = \frac{\nu}{a^2}\Delta^2\psi \qquad (9)$$

$$\frac{\partial}{\partial\theta}(v_\theta \sin\theta) + \frac{\partial v_\lambda}{\partial\lambda} = 0 \qquad (10)$$

where

$$\Delta \equiv \left\{\frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial}{\partial\theta}\right) + \frac{1}{\sin^2\theta}\frac{\partial^2}{\partial\lambda^2}\right\}$$

is the spherical-surface Laplacian operator; θ, λ, a are, respectively, the co-latitude, longitude, and radius of the spherical surface; v_θ and v_λ are, respectively, the velocity components in the directions of the gradients of θ and λ.

It can be shown that the following stream function

$$\psi(\theta, \lambda, t) = -\omega(t)a^2 \cos\theta + \left\{A_n P_n(\cos\theta) + \sum_{m=1}^{n} A_n^m P_n^m(\cos\theta) \times \cos\left[\lambda - \int \Omega_n(t)\, dt + B_n^m\right]\right\} e^{-\nu St} \qquad (11)$$

satisfies the vorticity equation (9). Here $\omega(t)$ is the relative angular velocity of the zonal current which is an arbitrary function of time; A_n and $A_n^m (m = 1, 2, \cdots, n)$ are $n + 1$ amplitude factors, and $B_n^m (m = 1, 2, \cdots, n)$ are n phase angles; $S = (1/a^2)n(n + 1)$ and

$$\Omega_n(t) = [1/n(n+1)]\{(n-1)(n+2)\omega(t) - 2\Omega\} \qquad (12)$$

is the angular phase velocity of the wave which depends on the angular velocity of the Earth Ω, angular velocity of the zonal current $\omega(t)$, and the degree of the surface spherical harmonic n. It is seen from (12) that if the relative angular velocity $\omega(t)$ is absent, the westward wave velocity increases with decreasing wavelength and increasing lateral extent of the waves. It is also seen from (12) that the effect of friction is to damp out the waves. No steady wave is possible in viscous flow over a spherical surface, since this condition would require $S = 0$. However, quasi-stationary waves, which may be defined as waves with zero wave velocity but changing wave amplitudes, may occur if

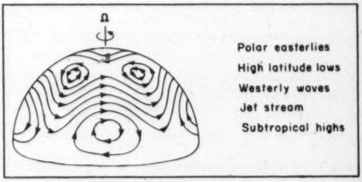

FIG. 3 – Stream-line pattern for quasi-stationary flow over a rotating spherical surface with $m = 4$ and $n = 5$

$$\omega = 2\Omega/(n-1)(n+2)$$

To illustrate the distribution of harmonic waves over a spherical surface, the streamline pattern of an example for the quasi-stationary case with $m = 4$ and $n = 5$ has been sketched in Figure 3. It is interesting to note the resemblance between the streamline pattern in the theoretical model and that in the actual upper level flow in the atmosphere. It is seen from Figure 3 that the streamline pattern consists of major characteristic features in the atmosphere such as subtropical highs, jet stream, westerly waves, high latitude lows, and polar easterlies.

Conclusion—A systematic analysis of planetary waves in a zonal current with jet stream, linear velocity-shear, and uniform angular velocity shows that (1) the phase velocity of the planetary waves in a zonal current with jet stream increases or decreases depends respectively on the narrowing and broadening of the jet stream, (2) the increase or decrease of the dimension of the planetary waves follows respectively the broadening or narrowing of the width of the jet stream, (3) the major effect of a linear velocity shear in a zonal current is to damp out waves in the current, (4) the streamline pattern in a zonal current on a spherical Earth with uniform angular velocity exhibits major characteristic features in the atmosphere such as subtropical highs, jet stream, westerly waves, high latitude lows and polar easterlies, and (5) the effect of viscosity is to damp out all waves in the current.

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Microvariations of Water Vapor in the Lower Troposphere with Applications to Long-Range Radio Communications

JOHN R. BAUER AND JAMES H. MEYER

Abstract—Variations of water vapor in the troposphere are calculated from simultaneous airborne measurements of radio refractive index and temperature obtained respectively with a microwave refractometer and an aerograph employing a sensitive bead thermistor. The partial pressure of water vapor is calculated from the well-known equation

$$e(\text{mb}) \cong 2.7(n-1)T^2 - 2.1 \times 10^{-4}PT$$

where n is the refractive index; T is temperature, °K; and P is total atmospheric pressure mb. The method is applied to the investigation of the horizontal and vertical structure of water vapor associated with a thin inversion layer found near 9800 ft pressure altitude. Evidence is offered for the vertical stability and absence of turbulent mixing of the air in the region of the inversion. When the reflection coefficient of the observed layer at radio wave lengths of 600 and 72 cm is computed at a range of 200 mi beyond the horizon, better than an order of magnitude agreement is obtained between the calculated and observed path losses at this range.

EXPERIMENTAL OBSERVATIONS

Introduction—The material presented in this paper is taken from the meteorological research being conducted by the radio propagation group at the MIT Lincoln Laboratory. The objective of this research work is to study the relationships between beyond-the-horizon propagation of meter and centimeter radio waves and the tropospheric weather. The scope of this meteorological research covers both the large- and small-scale variations of the meteorological parameters in the lower troposphere. This report is a study of refractive index, temperature, and calculated water vapor at a particular time and location along the New England coast on August 22, 1956. An Air Force C131-B Convair from Hanscom Field, Bedford, Massachusetts, equipped with an airborne refractometer and an aerograph system, and a Navy P2V from the Naval Air Development Unit, South Weymouth, Massachusetts, equipped with an airborne refractometer, participated in this particular experimental flight. The C131-B and the P2V made simultaneous soundings from 1000 to 10,000 ft pressure altitude at the ends of the predetermined 26.5-mi flight path shown on the map insert Figure 1. Pressure altitude, as used here, represents the quantitative value of the pressure at a given point by giving the height above a given standard pressure at which the pressure occurs in the standard atmosphere. An inversion found at approximately 9800 ft pressure altitude was probed by the C131-B, flying a saw-tooth pattern between 9400 ft and 9900 ft along the flight path from south to north. The saw-tooth pattern was flown for the purpose of exploring the vertical and horizontal distribution of refractive index, temperature, and water vapor associated with the inversion.

A brief description of the parameters measured and the instrumentation used is as follows: The Crain-type airborne refractometer was used to measure the radio refractive index. A Kollsman type KS-4 aerograph system in the C131-B was used to measure temperature, relative humidity, and absolute pressure. Sensitive barometric altimeters were used to measure pressure height. Since the instrumentation is considered capable of measuring microscale variations, the response times and observational errors of these instruments are of interest. An Esterline Angus recorder was used to record relative refractive index as measured by the refractometer. The time required for a complete change of air in the sampling cavity, that is, the 'cleanout time,' has been estimated to be approximately 10^{-2} sec at the operating airspeed of 2.5×10^2 feet/sec. However, since the magnitude of the frequency response of the metering circuit plus the pen recorder was given by the function $A(f) \cong A(0) \exp(-0.67f + 0.035f^2)$, where f is in cycles per second, and $0 < f \gtrsim 10$ cycles/sec, it is clear that refractive index fluctuations containing frequency components in excess of about two cycles/sec were strongly attenuated by the recording circuit. Under ideal flight conditions, the system noise was 0.1 N (an N unit is one part in 10^6 in tropospheric refractive index). Under certain flight conditions such as were some-

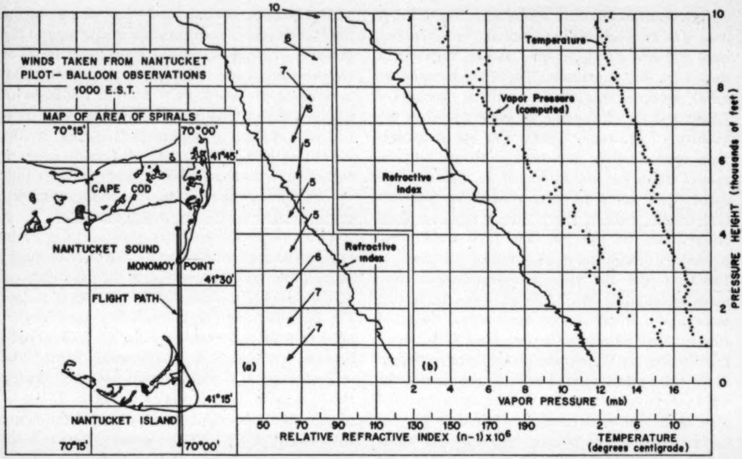

FIG. 1 – Refractive index, temperature, winds, and computed water vapor pressure observed over the Cape Cod and Nantucket, Massachusetts area on August 22, 1956: (a) spiral ascent at Monomoy Point by P2V, 13h 25m–13h 50m EST; (b) spiral ascent over Nantucket by Convair, 13h 25m–13h 50m EST

times encountered during climbing maneuvers, aircraft vibrations produced noise amplitudes as large as 1 N.

The thermister bead employed to measure temperature had a time constant of about four seconds. This time constant (not the temperature recorder) was the limiting factor in measuring temperature fluctuation rates. The noise amplitude in the servomechanism drive for the recorder was approximately 0.1°C. The pressure measuring system consists of an aneroid diaphragm mechanism with a servomechanism for remote indication. This system had a response time of about one second and a probable error of ±0.5 mb.

Calculation of water vapor from refractive index, pressure, and temperature—Since the refractive index measured by the refractometer is relative refractive index, the first step in calculating water vapor from the index data is to find the absolute refractive index. This was accomplished by computing the absolute refractive index from the aerograph temperature, relative humidity and pressure data at some point along the refractive index profile where the index was varying slowly with height. The following formula was used to compute the absolute refractive index at the selected point

$$N \cong (n-1) \times 10^6 \cong 77.6\,P/T + 3.73 \times 10^5 e/T^2 \qquad (1)$$

where P is total pressure in mb, n is radio refractive index, e is partial pressure of water vapor in mb, and T is absolute temperature. Once the absolute values of refractive index are known, the partial pressure of water vapor can be calculated by the formula

$$e \cong 2.68(n-1)T^2 - 2.08 \times 10)^{-1}PT \qquad (2)$$

where the variables are the same as those in the above formula. The temperature and total air pressure used to calculate e were those recorded by the aerograph. Under average summer conditions in the lower troposphere (300°K, 20 mb, water vapor pressure, and 1000 mb, total pressure) the rincemental relationship [*Gerhardt* and *Crain*, 1950] between radio refractive index, water vapor, temperature, and total pressure is given approximately by the relationship

$$\Delta N \cong 4.2\Delta e - 1.4\Delta T + 0.26\Delta P \qquad (3)$$

From this expression it is seen that the contribution of water vapor fluctuations to refractive index fluctuations is sixteen times that due to total air pressure fluctuations.

Flight area and profile measurements—Figure 1 shows the refractive-index profiles obtained from the simultaneous soundings made by the two aircraft. The temperature profile and the calculated water-vapor profile were taken from the C131-B data. The locations for the simultaneous soundings were the end points of the 26.5-mi flight path shown on the map insert. The C131-B made its spiral ascent a few miles south of Nantucket Island and the P2V made its spiral ascent in the vicinity of Monomoy Point. The spiral ascents were approximately five miles in radius, and the rate of climb was 400 ft/min at an indicated airspeed of 150 knots. In order to add more information to the analysis, the Nantucket pilot-balloon observations for the 10h 00m EST winds were plotted. Although the wind sounding was made at 10h 00m and the aircraft measurements were made around 13h 30m, there are some interesting observations which can be made about the wind structure and the aircraft measurements. However, this requires the assumption that little or no change in the wind profile existed between the time of the wind observations and the aircraft measurements. Also, there is an error in height which must be considered between the plotted height of the winds and the height of the aircraft measurements. The winds are plotted for mean sea-level heights and the other data are plotted for pressure heights. The pressure height was on the average 350 ft below the MSL height. Thus, if the plotted winds were shifted 350 ft down the height scale in Fig. 1, one would have approximately the correct fit of the winds to the other data.

Upon comparing the two simultaneous refractive-index profiles in Fig. 1, one can in general make some comparisons of the grosser features of the profiles below 8000 ft. Between 8000 and 1000 ft both the fine and large scale features of the two profiles are poorly correlated. The winds, if one assumes they apply to the data, suggest that there was little shear due to wind speed changes below 8000 ft. However, there is a large rotational change in the wind vector between 5000 ft and 8000 ft. The largest rotation occurs between 7000 and 8000 ft. The attendant rotational shear indicates the possibility of mixing in this height interval. The instability of the temperature lapse rate over a few hundred feet between 7000 and 8000 feet, and the absence of any large discontinuity in the refractive index in this height interval also suggests a well mixed layer of air.

When the assumption is made that the air is horizontally stratified, the temperature profile from the C131-B sounding gives a general over-all picture of the stability of the air sampled between one and 10,000 ft. The air sampled in this height interval was on the average conditionally stable with respect to vertical wind shear. However, the finer features of the temperature profile suggest the presence of many small and rapid fluctuations of temperature where the lapse rates over small increments of height vary from a condition of instability to absolute stability. The most pronounced change in temperature occurs in the vicinity of 9800 ft. The large shelf-type decreases in refractive index above 8000 ft clearly suggest that the phenomena present in this region extended continuously over the entire flight area.

Saw-tooth profiles and cross section—In order to explore the horizontal behavior of refractive index, water vapor, and temperature in the neighborhood of the temperature fluctuation near 9800 ft (see Fig. 1), a saw-tooth flight trajectory was executed between 9400 and 9900 feet along the 26.5-mi path between Nantucket and Monomoy Point. The original refractive index record obtained during this saw-tooth flight is shown in Figure 2. Beginning in the upper right- hand corner of the figure with ascent A we note the sudden fluctuation of refractive index from 219 *N* units to 207 *N* units between 9700 and 9750 ft. On descent B and all subsequent ascents and descents the index fluctuation is clearly present at approximately the same altitude. The small scale fluctuations seen on the ascent profiles but not on the descent profiles are due to communication of aircraft vibrations to the pen of the recorder during the powered climbs.

Figure 3 shows the refractive index, temperature, and calculated water vapor profiles for the individual slant ascents and descents made during the saw-tooth probing of the inversion in the vicinity of 9800 ft. The slanting heavy lines in Figure 4 show the computed flight path of the aircraft during its ascents and descents through the inversion while transversing the 26.5-mi path from south to north. The measurements shown on ascent A in Figure 3 were obtained along the trajectory shown by the first heavy slanting line (A) on the left side of Figure 4. Ascent A was made in the vicinity of Nantucket Island and descent F was made in the vicinity of Monomoy Point. Following the temperature profiles from ascent A through descent F, one may note the fact that the temperature inversion is well defined over the Nantucket area. However, as one moves toward Cape Cod the inversion becomes less sharp in its temperature gradient. Note the small differences in the heights of the moisture shelves among the individual ascents and descents. Following the refractive-index and vapor-pressure profiles through this series of soundings, we observe the rapid fall-off

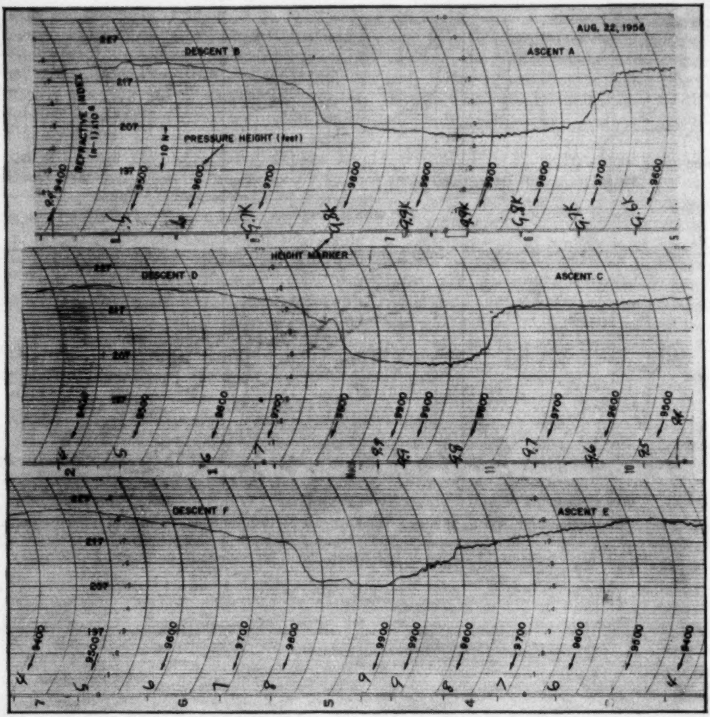

FIG. 2 – Original microwave refractometer record of radio refractive index observed during saw-tooth flight between pressure altitudes of 9400 and 9900 ft between Nantucket Island and Monomoy Point, Massachusetts, on the afternoon of August 22, 1956; note sharply stratified layer near 9800 ft

of both functions when the temperature lapse rate satisfies the condition of absolute stability ($dT/dz > 0$) [*Haurwitz*, 1941]. The total moisture fall-off in all the profiles, with the exception of ascent *E*, is on the order of two millibars, and the changes occur over a height difference on the order of a few meters. The homogeneity of the moisture above and below the inversion is another interesting feature of this data. Above the inversion the moisture remains at 2 ± 0.3 mb over the entire 26.5-mi flight path and below it remains at 4 ± 0.5 mb over this distance.

With respect to beyond-the-horizon propagation of meter and centimeter radio waves, *Gordon* [1955] has associated small scale turbulence with an inversion of this type. The homogeneity of the moisture above and below the inversion is strongly suggestive of the absence of turbulent motion within the layer. It would appear that this suggestion is strengthened by the condition of absolute stability of the temperature gradient across the layer, unless, of course, sufficient wind shear were present to produce turbulent motion. The pilot-balloon wind observations made at Nantucket four hours prior to the aircraft measurements (see wind profile, Fig. 1) indicated a positive wind-speed change of four knots between 9000 and 10,000 ft. If the assumption is made that these wind-speed

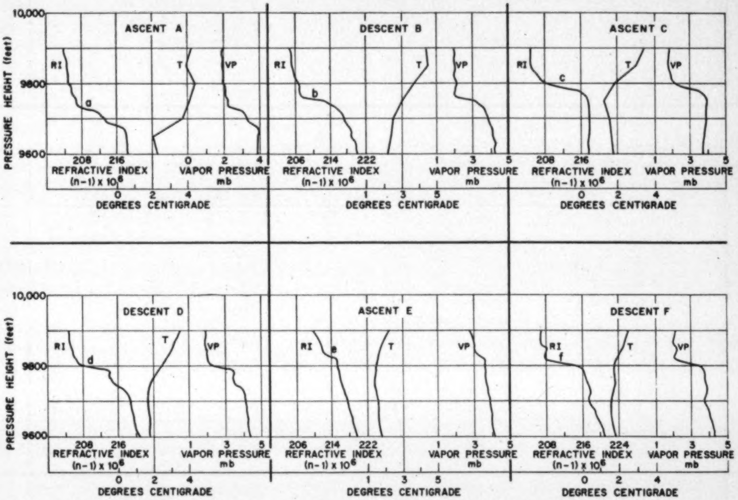

FIG. 3 – Saw-tooth profiles, Nantucket to Monomoy Point, August 22, 1956; individual profiles of refractive index, temperature, and computed water vapor pressure obtained during saw-tooth probing of inversion layer observed near 9800 ft between Nantucket Island and Monomoy Point, Massachusetts, on August 22, 1956

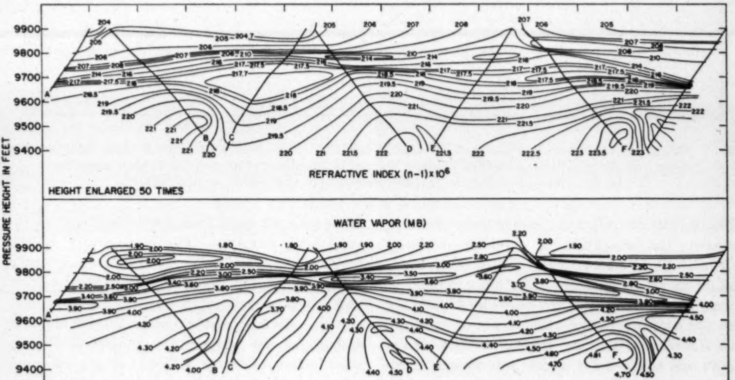

FIG. 4 – Saw-tooth cross sections between 9400 and 9900 ft (pressure altitude) showing contours of refractive index and water vapor pressure in the vicinity of inversion layer observed over 26.5-mi flight path between Nantucket Island and Monomoy Point, Massachusetts, on August 22, 1956

data are applicable at the time of the aircraft measurements, then the calculated values for the Richardson's numbers at the inversion levels of the saw-tooth profiles varied between 18 and 79 with an average of 36. Since Richardson's number need only exceed unity to reduce turbulent flow to laminar motion, these calculations further suggest the absence of turbulence across the inversion [*Sutton*, 1953].

The saw-tooth cross section presented in Fig. 4 is an attempt to show the vertical and horizontal distributions of refractive index and water vapor associated with the inversion between 9400 and 9900 ft over the 26.5-mi flight path. The cross section was made by linearly interpolating between the points of refractive index and water vapor plotted along the flight path with respect to time. The horizontal distance was calculated from time and ground speed of the aircraft. In order to represent the horizontal irregularities, the height scale is enlarged fifty times that of the horizontal scale. If the scale of this cross section were reduced to a one to one scale, the total 500-ft height difference would have to be compressed into a height interval comparable to one-tenth of a 100-ft height increment as shown in Fig. 4. Because of the close packing of the contours in the vicinity of the inversion, difficulty was experienced in trying to draw in all the one N-unit lines of equal refractive index and the 0.2 mb lines of equal vapor pressure. Therefore, many of the contour lines had to be omitted. However, if one notes the changes in the density of the contour lines of refractive index and water vapor, he can easily see the rapid fall-off of both functions with height. An important consideration to be made about this cross section is its resolution. The resolution of the data is better where the flight paths of the individual ascents and descents are close together. The resolution of this cross section could have been improved considerably by making one or two horizontal flights over the flight path at different altitudes between 9400 and 9900 ft. In future flights of this type, horizontal flights are planned to improve the resolution of the data. Upon relating the temperature profile of ascent E in Figure 3 with the horizontal and vertical distribution of refractive index and water vapor in the vicinity of ascent E in Fig. 4, one can see why the refractive index and moisture changes across the layer on the particular ascent were not as large as in the other profiles. The effect is clearly associated with the reduced temperature change at the inversion level. The contours in the vicinity of this temperature change suggest that some form of a disturbance was affecting the inversion at this particular location along the flight path. However, because of the limited quantity of data there is no positive identification for the type of disturbance which was present.

APPLICATIONS TO RADIO COMMUNICATIONS

Radio reflections from an idealized layer—Average yearly radio field intensities at wave lengths from a few centimeters to several meters at ranges from a few tens to several hundred miles beyond the horizon are tens to hundreds of decibels higher than can be accounted for on the basis of diffraction round the curved Earth [*Institute of Radio Engineers*, 1955]. The propagation is believed to arise principally from scattering by some type of dielectric inhomogeneity in the troposphere (0–10 km) or stratosphere (10–25 km) or both. *Booker* and *Gordon* [1950] have proposed that omnipresent isotropic turbulent eddies in the atmosphere scatter radiation beyond the horizon, while *Carroll* and *Ring* [1955] maintain that the main effect is due to a type of mode propagation through the smoothly tapered thick atmosphere.

Some years ago, *Smyth* and *Trolese* [1947] and *Saxton* and others [1951] showed that layers below 4000 ft reflected waves a few meters long to distances up to 92 mi beyond the horizon. More recently *Bauer* [1956] described refractometer measurements of extremely thin and distinct reflecting layers up to heights of three km in the lower troposphere which he estimated are capable of explaining the propagation of wave lengths from a few centimeters to several meters to distances up to 200 mi into the 'scatter zone.' The remainder of this paper is devoted to the question of the partial reflection potential of the stratified irregularity described.

Deferring for a moment the presence of horizontal irregularities in the layer shown in Figures 3 and 4, that is, assuming the layer is perfectly plane stratified, note that the variations with height z of refractive index across the profiles of the layer are rather well approximated by the function

$$n(z) = \frac{n_1 + n_2}{2} - \left(\frac{n_1 - n_2}{2}\right) \times \tanh\left(\frac{2z}{l}\right) \quad (4)$$

for which layer model the exact reflection coefficient was first worked out by *Epstein* [1930]. n_1 and n_2 are the refractive indices of the air just below and just above the layer, respectively. The origin of z is taken at the height of maximum gradient of the

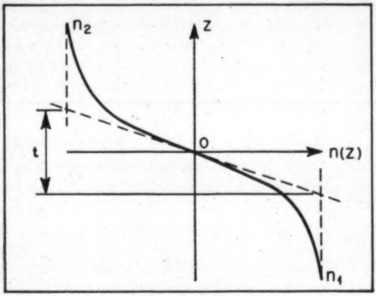

FIG. 5 – The refractive index model employed in computing the radio reflection from an elevated layer

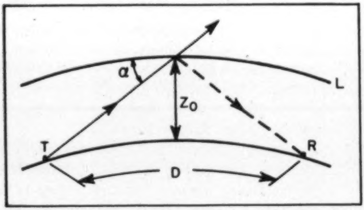

FIG. 6 – The geometry of single reflection from a layer to a receiving antenna *R* beyond the horizon

transition layer; the layer thickness t is defined as the difference in the heights of the intersections of the tangent to $n(z)$ at the middle of the layer and the index levels n_1 and n_2 (see Fig. 5). Let α be the glancing angle of incidence of a radio wave on the layer as shown in Fig. 6. For those relatively large values of α which characterize long propagation paths $\alpha^2 \gg 2(n_1 - n_2)$ [*Bauer*, 1956]. For this condition, most of the incident energy is transmitted through the layer and only a weak reflection is allowed. *Bauer* [1956] has shown that the power reflection coefficient ρ for the model we have chosen (Eq. 4) is given by

$$\rho \cong \left(\frac{n_1 - n_2}{2\alpha^2}\right)^2 \left(\frac{\pi m}{4}\right)^2 \left[\sinh\left(\frac{\pi m}{4}\right)\right]^{-2} \qquad (5)$$

where $0 \leq m = t/t_0 = \dfrac{4\pi\alpha t}{\lambda_0} \lesssim 1$, and λ_0 is wave length of the incident radio wave. Measurements made at Lincoln Laboratory, MIT, by *Chisholm* and others [1957] at a range of 188 mi with $\lambda_0 = 72$ cm show a yearly average path loss of about 62 db below free space, while *Abel's* [1956] airborne measurements at $\lambda_0 = 6$ m show a mean path loss of 45 db below free space at a range of 200 mi. From Figure 3 we take $n_1 - n_2 \sim 10^{-5}$, $t \sim 10$ m. Let the mean layer height be 9800 ft. When the correction for standard refraction below the layer is made, we find $\alpha \cong 2.8 \times 10^{-2}$ radians for the 200-mi range. From (5) we obtain a reflection coefficient of 4×10^{-5} at $\lambda_0 = 6$ m and 1×10^{-6} at $\lambda_0 = 72$ cm. These reflection coefficients predict path losses of 44 db and 60 db below free space for the 600 and 72 cm wave lengths, respectively, in close agreement with the observed path losses. In the microwave region, the 10-m thick layer described here is far too thick to account for the observed propagation to 200 mi; a layer no more than two meters thick is required [*Bauer*, 1956]. Evidence for the existence of such thin layers has been previously reported [*Bauer*, 1956].

Discussion of horizontal irregularities and layer size—The central theoretical difficulty associated with layer theory is the effect of horizontal irregularities in the dielectric structure, vis., horizontal changes in layer height, thickness, $n_1 - n_2$, etc. Such variations are clearly seen in Fig. 3. According to Rayleigh's criterion [*Kerr*, 1951] a surface may be considered a plane specular reflector when the unevenness Δh does not exceed approximately $\pm\lambda_0/(4\pi \sin\alpha)$ over a Fresnel zone. For our example of propagation to 200 mi via a 9800-ft layer, this criterion requires that the unevenness at 600 and 72 cm should not be much larger than ±55 ft and ±6 ft, respectively. The Fresnel zone for our example (range $D = 200$ mi, $\alpha = 2.8 \times 10^{-2}$ radians) is an elliptically shaped patch of length $l \geq (D\lambda_0)^{1/2}/2\alpha$ and width $w \geq l\alpha$ [*Bauer*, 1956]. For $\lambda_0 = 72$ cm, the required dimensions w and l are 0.15 and 5.3 mi, respectively, while for $\lambda_0 = 6$ m, w and l must be 0.43 and 15 mi, respectively. A study of Figures 3 and 4 shows that the center of the layer (height of maximum index gradient) varies smoothly by about ±50 ft over a horizontal distance of 26 mi. Thus the entire layer appears to satisfy the Rayleigh criterion for $\lambda_0 = 6$ m. While the resolution of the data is insufficient to determine the height variations required for the 72-cm wave reflections, the linear interpolations of Figure 4 strongly suggest the presence of several smooth patches a few miles long which are smooth enough to reflect at this wave length. At both wave lengths, however, the layer must be considered a slightly warped reflector which could hardly be expected to support a good image.

In conclusion we emphasize that insufficient meteorological and radio data are available to establish the extent to which stratified layers support long-range short-wave communications through the troposphere. Available airborne meteorological data indicate that during good flying weather there are almost always some stratified layers in the troposphere. During very cold, dry, or unstable weather, scattering from poorly stratified or somewhat isotropic irregularities may play an important role in tropospheric short wave radio propagation well beyond the horizon.

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A Theoretical Analysis of Sea-Ice Strength

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Abstract—For the first time an attempt is made to derive a theoretical relationship between sea-ice strength and the controlling factors of salinity, temperature, and density. A geometric model of the ice-brine relationship is constructed from photographs and used to calculate tensile strength of warm (above −20°C) sea ice. The theoretical results compare well with experimental data. The model developed can be extended to colder temperatures by considering the effect of solid salts.

Background—When sea water freezes, small flat plates of pure ice form, leaving behind a concentrated brine which tends to drain out of the ice. However, a certain amount of the brine is retained between the ice plates in layers or pockets, causing the sea ice as a whole to be salty. In general, the faster the ice grows, the more brine is trapped. When the ice first forms, the flat ice plates float on the surface of the water with their c axes vertical, forming a very weak, highly saline mush of overlapping plates. As the ice thickens the plates grow at an angle to the surface, and, at about 1.5 cm from the top, depending on the freezing conditions, vertical plates, with the c axes horizontal, predominate. In lake ice, on the other hand, the c axis often remains vertical throughout the thickness of the ice, and long, candle-shaped crystals are formed. The small plates alternating with layers of brine occur in bundles which appear as single crystals under crossed polaroids.

The temperature and salinity of the ice determine the amount of brine and hence the thickness of the brine layers. The salinity of the brine is much greater than that of the original sea water and depends on the temperature of the surrounding ice with which it is in thermal equilibrium. As the sea ice becomes colder, more ice freezes out of the brine, which becomes more concentrated. With a temperature rise, ice melts and the brine becomes diluted. These brine layers shrink as the temperature decreases and finally 'neck' and separate into vertical cylinders which often extend entirely through the ice sheet. These brine cylinders are separated by ice 'bridges' which connect the original plates. The separation of the layer is controlled predominantly by surface tension. The cylinders are therefore circular or elliptical in horizontal section. The process of the brine-layer separation into cylinders is shown diagrammatically in Figure 1. The hatched area is brine.

Figure 1a is a horizontal section (plan view) showing ice plates separated by brine layers. In Figure 1b the brine layers have begun to 'neck,' and in 1c the brine layer has separated into cylinders. Figure 1d shows the orientation of elliptical cylinders—the short axis of the ellipse is always perpendicular to the ice plates. With a further temperature drop the radii of the cylinders decrease. In the case of elliptical cylinders the long axis shrinks faster than the short, and the cross section approaches a circle. Figure 2a is a photograph of a horizontal section of sea ice in which the layers have begun to 'neck.' In Figure 1c and 2b the layers have split into rows of cylinders. Figure 2d is a vertical section of the same ice. Note the length of the brine pockets. Figure 1f is a three-dimensional schematic sketch of the ice-brine relationship. Fig. 2c shows badly deteriorated ice.

Ideally, a row of equally spaced, equal-diameter, circular cylinders will be formed. Actually, ellipses are more common, and spacing and dimensions vary widely. Often the brine layer splits into two or more parallel rows of cylinders. The possible complexity of the broken brine layer is evident in the photographs.

These cylinders stay long in relation to their diameter because of gravity and the thermal gradient across the ice. They are unstable and migrate to the warmer temperature, which in winter is the lower surface of the ice [see *Veinberg*, 1940]. This causes brine to drain out of the ice even under very cold conditions. The salinity of the ice therefore decreases from its initial value of 15 to 20‰ to about 5‰ late in the first season. The various constituents of the brine crystallize out as their eutectic point is exceeded. Sea ice probably never becomes completely solid under natural conditions. The presence and geometry of these brine pockets are the controlling factors in the strength of the sea ice. The present analysis is limited to warm ice. No attempt is made to determine the quantitative effect of solid salts.

When sea ice breaks in tension or flexure, it

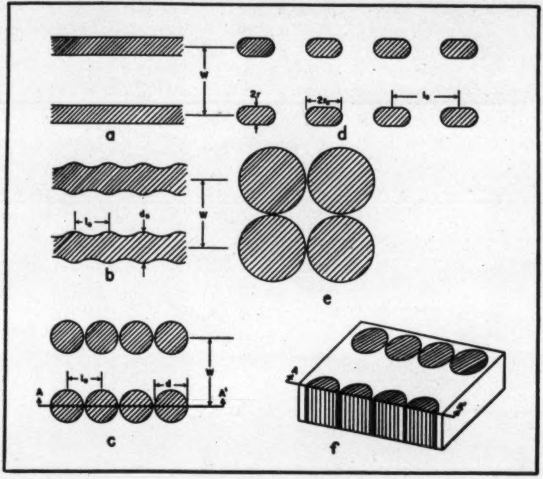

FIG. 1 – Schematic diagrams showing how a brine layer splits into cylinders; see text for details

breaks primarily along these brine cells, parallel to the small plates. Figure 3 is a rubbing of a horizontal section of an ice beam that has been broken. The parallel lines are the edges of single plates. Each group of parallel lines is a crystal. Sea-ice failure surfaces are usually irregular because of this tendency to break along the plate boundaries.

Sea-ice model—To derive a theoretical relationship between strength and the controlling factors of salinity and temperature, we shall use the above information to construct a simplified model. We will consider the strength in tension since a loaded ice sheet usually fails in tension.

Consider a small, thin slab of sea ice in which the brine cylinders go all the way through. In Figure 1c let A–A' be the line of break. The direction of tension was at right angles to this line. The strength of the ice depends on the area of the cross section normal to the tension. Because of the presence of the brine the effective cross-sectional area is reduced.

Let $\beta_e = d/l_o$ where β_e is the amount of brine in a unit area of the failure plane, d is the diameter of the cylinders, and l_o is the cylinder separation in the failure plane (Fig. 1). The effective width of the area is then $(1 - \beta_e)$, considering unit thickness. In the case of ellipses, $\beta_e \cong 2r_e/l_o$.

The strength of the sea ice σ then will be a function of the form

$$\sigma \sim \sigma_p\,(1 - \beta_e) \tag{1}$$

where σ_p is the strength of the ice with no brine cells, that is, pure ice.

The brine cells also act as stress concentrators. The highest stress will be on the edge of the cylinder normal to the direction of tension, and this will be the point of initial failure. A single, round, cylindrical hole in an infinite plate will have a tangential stress on its boundary equal to three times the applied stress. An elliptical hole with its long axis normal to the tension will have an even larger stress concentration [see, for instance, *Timoshenko*, 1934]. The failure surface will spread perpendicular to the direction of tension—in this case, along the row of holes. The apparent strength of a slab in the vicinity of a hole is one third of the strength with no hole. Actually, with only a few holes the strength may not be reduced to this extent except under repeated loadings. The crack will spread slightly with each loading, and finally the slab will fail by fatigue. With the numerous 'flaws' in sea ice, however, the cracks intersect, and we may consider that the strength under single loading is immediately reduced.

The stress-concentration factor k is defined as

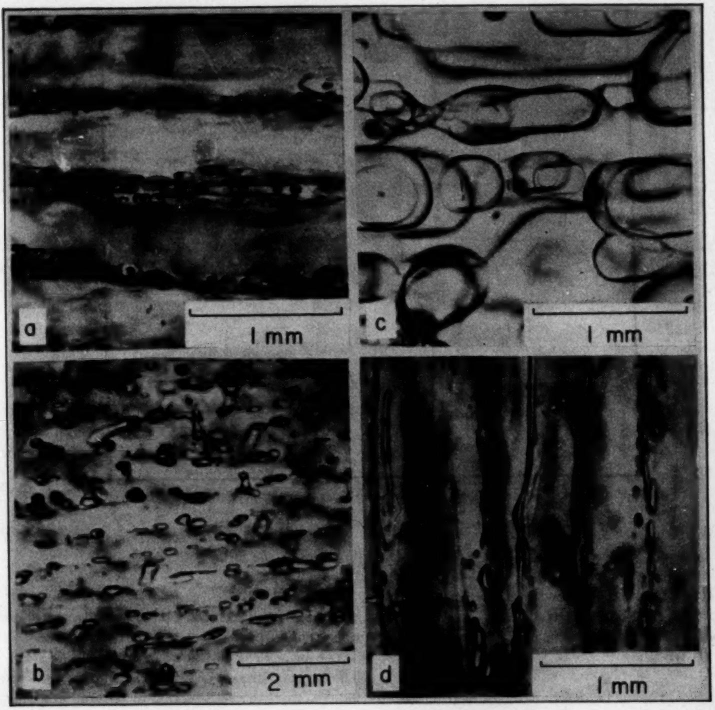

FIG. 2 – Photomicrographs of sea ice, showing brine-ice relationship

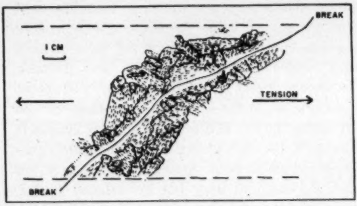

FIG. 3 – Rubbing of a broken segment of sea ice

the ratio of the maximum stress to the average stress in the minimum section. The stress in the minimum section is the force on the end of the slab divided by the effective cross-section area.

Thus, considering the ice at its breaking point

$$k = \sigma_p(1 - \beta_e)/\sigma \qquad (2)$$

This puts the strength equation in the form

$$\sigma = \sigma_p(1 - \beta_e)/k \qquad (3)$$

When the ice is very cold and the brine pockets are small and far apart, we have essentially isolated holes in an infinite plate. As the ice warms and the brine pockets become larger and their edges closer together, the stress concentration factor decreases rapidly. There are, however, usually many small brine pockets scattered between the large ones; these are remnants of the brine that went to form the large cylinders. These small cylinders are effective stress concentrators and will always have a stress concentration at their boundary of approximately three. The relation between strength and β_e is shown in Figure 4 for a row of equally

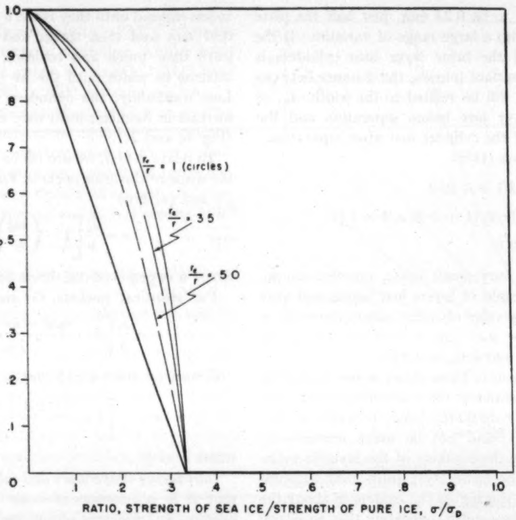

FIG. 4 – The effect on the strength of the amount of brine (β_e) and brine orientation along the failure plane

spaced circles and also for a row of ellipses with different axis ratios. The curves, for the most part, are sketched from experimental data of *Frocht* [1935] and Capper [*Howland*, 1935] and a theoretical solution by *Howland* [1935].

As the long axis of the ellipse increases, the curves approach the straight line which represents a constant stress concentration of three, the case where there are always small 'remnant' cylinders. This straight line gives the minimum strength at all times; the curve representing the row of circles gives the maximum. Since the ice will break where the strength is minimum, we shall use the straight line which represents a constant stress concentration of three. The curves all approach 0.33 on the abscissa because with a small brine content the brine pockets are mostly circular.

The slopes of the curves are discontinuous at $\beta_e = 0$ and jump to the strength of pure ice. As β_e approaches unity, the strength goes to zero. When β_e is small but the ice is still warmer than approximately −20°C, the strength is one-third that of pure ice. In very cold ice this strength reduction appears only upon repeated loading, as mentioned above. Note that lake ice is not necessarily 'pure' ice because of the presence of minute flaws.

Other factors tend to depress the strength value from the ideal row of circular holes. Unequal spacing, varying diameters, and irregular shapes will all increase the stress concentration and decrease the effective cross-sectional area.

Measurements from photographs—If l_0, the brine pocket separation, has a relation to W, the plate width, or if W is constant, then β_e can be related to β, the brine content by volume, of the ice. From about 50 measurements on photographs of sea ice under many conditions from a variety of locations, W was determined to be 0.46 mm with a small deviation from this value. Several measurements by *Fukutomi* and others [1952] show an average value of 0.39 mm. *Nakaya* [1956] describes a layer structure in pure ice crystals revealed by Tyndall figures. He determines the mean width of these plates to be 0.5 mm. Apparently the plates forming sea-ice crystals are equivalent to the plates in pure ice, but because of the brine layers the plate structure in sea ice is much more evident. This also suggests that impurities cause the plate structure in 'pure' ice.

A similar number of measurements from photographs of brine layers which have broken into round cylinders show the average distance between cylinders, l_o, to be 0.23 mm, just half the plate width, but with a large range of variation. If the separation of the brine layer into cylinders is governed by surface tension, the distance between the cylinders will be related to the width, d_o, of the brine layer just before separation and the diameter d of the cylinder just after separation.

From *Nakaya* [1956]

$$d/d_o = 2(1 + \epsilon) \cong 2$$

$$l_o/d = (\pi/2)\ (1 + \epsilon) \cong \pi/2 = 1.57$$

$$\therefore\ d_o/l_o \cong 0.32$$

where ϵ is a very small value, not determined. From photographs of layers just before and after splitting, an average of many values shows d_o = 0.07 mm, l_o = 0.23 mm, d = 0.136 mm, giving $d_o/l_o = 0.30$, and $d/d_o = 1.94$.

The agreement of these ratios seems to indicate that surface tension is the controlling factor. This agreement is remarkably good, considering that measurements could not be made immediately before or after the breaking of the layer in cylinders. When the brine layer splits into elliptical cylinders, the spacing of the centers is about the same as the plate width, indicating that an ellipse is simply two joined circles. As the ellipses shrink, they may break again. When a brine layer splits into ellipses, the short dimension $2r$ stays about 0.07 mm.

Converting to brine content—The brine content β of the ice is the ratio of the volume of the brine to the total volume. In the case of round cylinders

$$\beta = \tfrac{1}{4}\pi d^2/l_oW = \pi d^2/4a\, l_o^2 = \pi\beta_e^2/4a \qquad (4)$$

where $a = W/l_o$.

For 'elliptical' cylinders [not true ellipses]

$$\beta = \{\tfrac{1}{4}\pi(2r)^2 + (2r_e - 2r)(2r)\}/l_0W$$

$$= \frac{\pi r^2 + (\beta_e l_0 - 2r)(2r)}{al_0^2} \qquad (5)$$

Just before the layer breaks into cylinders $\beta = d_o/W \cong 0.07/0.46 \cong 15.2$ pct by volume.

This indicates that ice with more than about 15.2 pct by volume of brine has no strength. This no-strength condition is the skeleton layer phenomenon mentioned by *Weeks* and *Anderson* [1958]. The skeleton layer, then, has a brine content of at least 15.2 pct by volume. This high brine content on the bottom of the sheet is due to high salinity caused by brine drainage and the high temperature of the underlying water.

When very cold ice is warmed, the brine cylinders expand until they reach a diameter of about 0.07 mm and then spread out along the plates until they touch and coalesce. The layers then increase in width until the ice is entirely melted. Less commonly, the cylinders stay circular and increase in diameter until they touch and coalesce (Fig. 1e and 2c).

To relate σ to β, we use (4) or (5), depending on the shape of the brine pockets. For circular pockets, (3) and (4) give

$$\sigma = \frac{\sigma_p}{k}\left[1 - \left(\frac{4a\beta}{\pi}\right)^{\frac{1}{2}}\right] \qquad (6)$$

where a depends on the brine-pocket separation.

For 'elliptical' pockets, (3) and (5) give

$$\sigma = \frac{\sigma_p}{k}\left[1 - \frac{al_0^2\beta - \pi r^2 + 4r^2}{2rl_0}\right] \qquad (7)$$

Since l_o, r, and a are all measured, this reduces to

$$\sigma = \frac{\sigma_p}{k}\left[1 - \frac{0.2116\beta + 0.0011}{0.0322}\right] \qquad (8)$$

where $a = 1$.

Introducing temperature and salinity—Brine content β is a function of both temperature and salinity. In m grams of sea ice of salinity S_i‰, there are n grams of brine of salinity S_b‰ [*Malmgren*, 1927].

$$n/m = S_i/S_b \qquad (9)$$

where $n/m = \beta_w$ (pct brine content by weight). This formula holds until solid salts begin to pre-

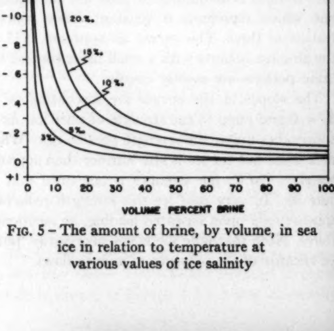

FIG. 5 – The amount of brine, by volume, in sea ice in relation to temperature at various values of ice salinity

cipitate. It is fairly accurate to −22.9°C when the sodium chloride starts to crystallize. At this point approximately 3.2 grams of $Na_2SO_4 \cdot 10H_2O$ have already precipitated in 1000 grams of sea ice.

With every S_b there is associated a temperature, because of previously noted equilibrium considerations; and with every temperature there is associated a density of pure ice, a density of brine, and, combining the two, a density of sea ice.

The relation between β and β_w is [*Veinberg*, 1940]

$$\beta = d_i \beta_w / d_b \tag{10}$$

where d_i = density of sea ice, and d_b = density of brine.

Therefore, knowing the temperature and salinity of the ice we can determine the brine content by volume, which we have already related to strength. Brine content by volume is plotted against temperature for various salinities in Figure 5. A more accurate curve, taking into account solid salts, has recently been developed by one of the authors (unpublished manuscript by DLA, Some Properties of Sea Ice).

The only quantity now lacking in (7) and (8) is the strength of pure ice. The best experimental values for the tensile strength of pure ice were obtained by *Butkovich* [1954]. His values for the relation of tensile strength of pure ice to temperature are essentially the same as those of *Wilson* and *Horeth* [1948] in flexure. Butkovich's values are used as the starting points in our curves, although they must be considered as only a first approximation to the actual strength of the small ice bridges. Butkovich's values are not obtained from perfectly pure ice and we also know that very small volumes give a higher strength than larger volumes. We can, however, obtain relative strengths by using these values. Pure ice may be up to three times as strong as reported by Butkovich.

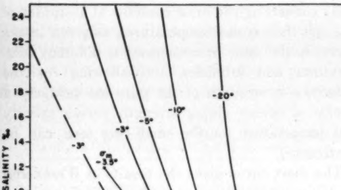

FIG. 6 – The relation between tensile strength and salinity at various temperatures for circular splitting of the two different cylinder spacings

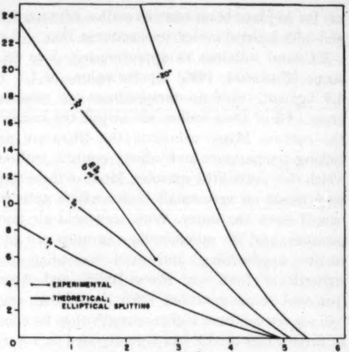

FIG. 7 – The relation between tensile strength and salinity at various temperatures for elliptical splitting

Values for strength versus temperature and salinity are plotted in Figures 6 and 7. Figure 6 assumes that the brine pockets enlarge as circular cylinders until they coalesce. Two different cylinder spacings are plotted for $t = -3$°C. The lower dashed curve is for $a = 2$; the solid curves for $a = 1$. The short curve shows experimental data [*Weeks* and *Anderson*, 1958]. Figure 7 assumes that the cylinders remain circular until $d = 0.07$ mm and then expand as ellipses. This happens when β is 3.6 pct. Spacing does not appreciably change the curves in this latter figure. As stated before, the ellipses are more common, and, since they cause lower strength, they would be expected to be especially common along the line of break. The value of k is assumed to be a constant three in the two preceding curves. The short curve is from the experimental data. In the experimental analysis the average temperature of the entire ice sheet was used. The beam tests are not directly comparable with theoretical results in tension. The result of stress concentration at the end of the cantilever has been ignored, and a constant cross section has been assumed in the experimental work.

Other investigators—Butkovich [1956] reports values for in-place beam tests on sea ice between 2.21 and 3.98 kg/cm² for ice temperatures from −5 to −8°C and salinities of approximately 5 to 8‰. Assur [*Butkovich*, 1956] reports values of 1.1 to 4.9 kg/cm², with no temperatures or salinities given. All of these values are within the areas of the curves. Many values in the literature are lacking temperature and salinity control, without which they have little meaning. Most of these tests were made on very small beams which were removed from the water. With very cold air temperatures and low salinities these samples can give results approaching and even exceeding the strength of fresh ice. *Petrov* [1955] and Assur (personal communication, 1956) report that very cold sea ice can have higher strength than lake ice. In these cases the ice has been exposed to a very cold air temperature, and the solid salts act as binders rather than stress concentrators. The warm underside of the ice is the point of initial failure under most conditions in situ. In the ice sheet the majority of the ice never experiences extreme cold because of the presence of the warm water. Also the different orientation of the crystals in sea ice would affect the strength.

Butkovich [1956] also reports results of small-ring tensile tests on sea ice. These values show a greater strength than the in-place tests reported by him and are also higher than the present writers' values. The small-ring tensile tests cause a break parallel to the applied force and extending between the points of application of the force. The break, then, is forced to cross crystal and plate boundaries, causing a much higher apparent strength. A statistical study of the plate size and orientation would permit a maximum, minimum, and average strength to be calculated, using the theory developed in this paper. Also, other type strength tests may be approached similarly.

Small beam tests seem to give values approximately 2.6 times greater than in-place cantilevers. Ring tests give results up to four times higher.

Even if the results of the two methods of testing are not at present directly comparable, they should give a similar strength, temperature, and salinity relationship. Butkovich performed 137 ring tests under a variety of temperatures and a small range of salinities, making them very valuable for giving the temperature dependency of the strength of sea ice. Plotting temperature versus strength for his ring tests for a constant salinity of 5‰ gives us the curve to the right in Figure 8. Each point is an average of about ten values. The curve indicates that, for a decreasing temperature, strength increases rapidly at first and then more slowly. The theoretical results (curve at left) show a similar tendency and compare reasonably well, remembering that we are not comparing values of strength but changes in strength with temperature. The inflection point for both curves is about −5°C. Extrapolating the experimental curve to no strength gives us, very roughly, 11 pct brine by volume (Fig. 5).

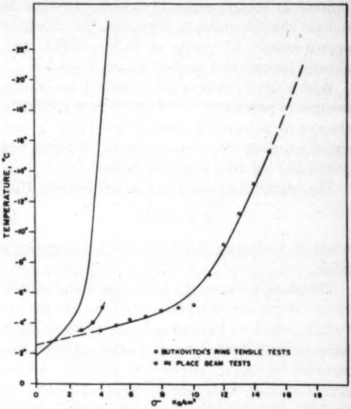

FIG. 8 – Relation between temperature and strength for sea ice of a salinity of 5‰; the solid curve is theoretical, elliptical splitting

By converting the brine contents at a salinity of 5‰ and the various temperatures, as given in the curve, to the same brine content at different temperatures and salinities, and allowing for the difference in strength of the pure ice 'bridges,' a family of curves giving strength versus salinity and temperature for the small-ring tests can be constructed.

The short curve gives the results of *Weeks* and *Anderson* [1958]. Because of the limited temperature range available in thin, in-place beams, this curve is very rough, but it extrapolates to about the same brine content at no strength as predicted in the theory.

Effect of enclosed air—The air content of sea ice can be very considerable. The air bubbles tend to concentrate in the brine pockets, and they have approximately the same effect on strength as adding a similar amount, by volume, of brine. Ice that has formed very rapidly under very cold conditions, or ice that has formed under turbulent conditions, is especially able to trap a large amount of air. Therefore, most of the air in young ice is near the top. As ice ages, the brine drains out and is largely replaced by air, giving old ice a considerable air content throughout its thickness.

The air content is reflected in the density. As stated before, the temperature and salinity completely define the density of air-free ice. The difference between measured and computed density is due to air. The air content can simply be added to the brine content when roughly calculating the strength of sea ice.

The density of warm sea ice can be obtained from (9) and (10).

$$d_i = \beta d_b S_b/S_i \tag{11}$$

Values of sea-ice density are published in *Malmgren* [1927], *Sverdrup* and others [1942], *Zubov* [1945], *Veinberg* [1940], and *Dorsey* [1940], as well as in some standard engineering and oceanographic tables.

In a sample computation for ice of 5‰ salinity and temperature of −7°C, the density is determined to be 0.925. If the measured density is, for instance, 0.920, then 0.005 grams of brine per cubic centimeter of ice have been replaced by air and we must add $(0.005/d_b \times 100)$ pct to the brine content obtained from the measured salinity and temperature. This calculation will also take into account original air. Because of the inherent inaccuracies of measuring density, temperature, and salinity, we can assume d_b to be one gram per cubic centimeter and thus convert the difference in density immediately to extra brine content because of air. Thus, from Figure 5 a temperature of −7°C and salinity of 5‰ gives a brine content by volume of 4 pct. Adding to this 0.5 pct for the air gives us a β for computation purposes of 4.5 pct by volume.

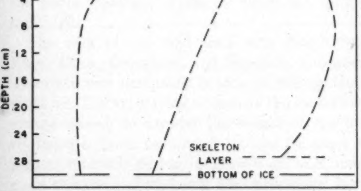

FIG. 9 – Typical salinity, temperature, and strength profiles through a sea-ice sheet

Conclusions—Because of the complexity of sea ice the derived formulas and curves are necessarily very general, but they give a first and, we believe, an accurate picture of the relation between strength and the major controlling factors.

The following considerations enter into a more detailed analysis of sea-ice strength:

(1) Surface tension probably has an appreciable effect on the cohesion of the ice plates.

(2) Sometimes the brine pockets do not entirely pierce the section under consideration vertically. This will not materially change the argument for tension, since for a given β_e the effective cross-sectional area will be the same, regardless of distribution of the brine. However, as can be seen from the flexural strength formula, the distribution of the brine materially affects the results of flexural calculations. If the brine pockets do not entirely pierce the section then the effective thickness, as well as the effective width, will be changed.

(3) The argument is developed for thin sheets in which the temperature and salinity are constant throughout. A thicker sheet is made up of many layers, each with its own temperature, salinity, and strength. A complete analysis of the strength of thick ice must include a variation of the constants throughout the section. A variable cross section should be used in calculation. Figure 9 gives a typical temperature and salinity profile through the sheet, and a strength profile using results from Figure 7.

(4) The geometry of the brine pockets, especially along breaks, must be studied further. The constants a, $2r$, and k can be changed, if necessary, as a result of further measurement, and perhaps the factors controlling the magnitude of these constants can be determined.

(5) The assumption of a constant k may fall down at high brine content when all the brine pockets are large, and at very low brine content. The theoretical strength at high temperature and salinity may be too low. The theory is general enough to include changes in stress concentration.

(6) The effects of plasticity and recrystallization have not been considered.

(7) Only breaks parallel to the small plates have been considered. Certain small-scale strength tests cause the ice to artificially break across the plates. Other tests load the ice parallel to the optic axis or to other directions which do not occur in an in-place ice sheet. Also, shear, torsion, impact, and compression tests are commonly performed. These tests can also be considered theoretically. Tensile,

or flexural, strength is usually the only strength property that is important in calculating the bearing strength of an ice sheet. The tensile strength of the warm underside of the ice is the most important single quantity.

(8) Inter-plate slippage may prove to be an important factor, especially in slowly applied loads.

(9) The quantitative effect of solid salts on very cold ice has not been considered in the present analysis. Work is continuing on this problem.

(10) 'Pure' lake ice itself has many stress concentrators, mostly minute air bubbles. If it is determined that these stress concentrations actually affect the strength by a factor of three, the numerical results reported in this paper are low. The formulas developed are still valid until solid salts precipitate in quantity but a higher value of σ_p must be used in numerical computations. σ_p refers to absolutely pure ice and has probably never been measured except possibly on very small samples. The ability of warm ice and ice next to the liquid phase to maintain a stress concentration must be studied. If the ice is not perfectly elastic, we would expect the stress concentration to be low in warm ice and to approach three in colder ice.

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An Experimental Study of Strength of Young Sea Ice

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***Abstract*—Values for the strength of sea ice are extremely sparse in the literature, and available values show a wide, unexplained variation. Results of in-place cantilever beam tests presented in this paper show a definite relationship between flexural strength and brine content. Values for Young's modulus are also experimentally determined. It is shown that the bearing capacity of a sea-ice sheet is dependent on the brine content and that thin ice sheets are capable of supporting a large 'super load' beyond the force necessary to form the first crack.**

Introduction—Detailed studies of the basic physical properties of sea ice are very few. *Malmgren's* [1927] work still remains the standard reference. In particular, information regarding the strength characteristics of sea ice is noticeably absent. Inasmuch as increased activity in the polar regions during IGY has necessitated the use of unprepared sea-ice surfaces as floating platforms for scientific activity, the bearing strength of sea ice has become an extremely critical problem.

The specific objectives of the present study are: (1) to determine the relations between the flexural strength and Young's modulus of sea ice and such parameters as ice temperature, salinity, and density; (2) to calculate the bearing capacity of young sea ice; and (3) to develop theoretical relations for the analysis of sea-ice strength based on the observed distribution of brine and air pockets so that it will be possible to extend experimentally determined strength curves.

The present study considers only in-place cantilever tests on thin (<40 cm), newly formed sea ice. This material was chosen since there is a large variation in its brine content and it is thin enough so that a large number of strength tests could be performed in a reasonable amount of time. This was considered necessary since previous work by *Petrov* [1955] has shown that the results of small sample strength tests on sea ice show a large scatter. Also, these tests duplicate conditions on the warm underside of the ice where the ice initially fails.

The sites of the field tests were North Star Bugt, Thule, Greenland, and Hopedale, Labrador. The tests were performed in areas of homogeneous sheet ice. Testing started as soon as the ice became strong enough to support the weight of the test equipment. Tests were made on this ice sheet at regular intervals during its growth up to a maximum thickness of 40.2 cm. This procedure, however, made it possible to collect only a very small amount of information during the freeze-up period since at any given ice thickness the ice can be tested at only one temperature and salinity. To avoid this difficulty, a number of large ponds (rectangular ice-free areas) were cut in the ice. These ponds were allowed to freeze on different dates so that ice of varying thickness and salt content could be tested during a period of a given air temperature.

The majority of published sea-ice strength tests have been made using small samples that were removed from the ice sheet and allowed to reach equilibrium with the air temperature [*Butkovich*, 1956; *Petrov*, 1955; *Veinberg*, 1940]. This type of testing is not suitable for studying very young sea ice, because when the specimen is removed from the water (1) a large portion of its brine content is lost by drainage; (2) it is often not capable of supporting its own weight; and (3) it is impossible to re-establish the exact in-situ temperature gradient. Also, the results of in-place, cantilever tests show a much smaller scatter than most small-sample tests [*Butkovich*, 1956]. Therefore all the tests were performed in place in the ice sheet so that the physical properties of the specimen would be identical to those of the over-all sheet.

Flexural strength—The general technique for obtaining the in-place flexural strength of sea ice was used by *Neronov* [1946] and other Russians, earlier, to measure the flexural strength of lake ice. First a U-shaped channel is cut in the ice sheet with an ice-pond saw. This channel isolates an in-place cantilever ice beam with one end attached to the sheet. Both pull-up and push-down tests were performed on these beams. On the pull-up tests a chain is placed around the end of the ice beam and attached to the end of a wooden lever. A force is then applied by rolling a heavy barrel from the fulcrum to the end of the lever. From the weights and positions of the chains, lever, and barrel at the time the ice beam breaks, the force applied to the end of the in-place beam can readily be computed. When the ice was very thin, the force was applied manually, using a dynamometer to measure the force at the end of the ice beam.

The push-down tests were performed using an additional lever that was anchored to the ice sheet. This lever transmitted a downward force to the end of the ice beam. When push-down tests were made on thin ice, a known weight attached to a dynamometer was lowered manually onto the end of the ice beam. In this case the force at the time of failure is simply the known weight minus the dynamometer reading.

The cantilever beam width was kept roughly ½ to 2 times the ice thickness and the length between 3 and 6 times the ice thickness. The average loading rate during the tests was 0.5 kg/cm^2 sec.

After failure the broken segment of the ice beam was immediately removed from the water and three measurements each were made of its length and its height and width at the failure cross section. Three measurements were necessary because of the irregularity of the break. A 7.6-cm diameter vertical core was taken from the sheet in the area of the tests, for the determination of a salinity profile. The ice samples from the core were immediately

TABLE 1 – *Results of in-place cantilever beam tests*

Test series	Date	Type of test U = pull up D = push down	No. of tests	σ	S Stan. dev.	σ_k	σ_m	Av. sal.	Aver. ice temp.	Ice thickness	Skel. layer	Ice type S = sheet P = pond
				kg/cm^2		kg/cm^2	kg/cm^2	‰	°C	cm	cm	
1	Oct. 29, 1956	U	2	0.72	0.14	1.19	1.40	10.7	−2.4	12.7	3.6	S
2	Oct. 31, 1956	U	6	1.70	0.15	2.45	2.75	10.4	−4.2	16.8	3.6	S
3	Nov. 1, 1956	U	7	1.50	0.19	2.07	2.24	8.8	−3.0	18.8	3.3	S
4	Nov. 2, 1956	U	5	1.25	0.16	1.68	2.10	8.9	−3.6	20.1	5.0	S
5	Nov. 3, 1956	U	7	1.36	0.06	1.82	2.11	8.3	−2.4	20.5	4.0	S
6	Nov. 5, 1956	U	3	1.05	0.07	1.34	1.47	8.1	−3.4	23.6	3.6	S
7	Nov. 6, 1956	U	3	1.15	0.10	1.47	1.63	8.0	−4.7	24.1	3.8	S
8	Nov. 6, 1956	U	7	0.86	0.04	2.16	1.91	13.0	−3.5	7.6	2.5	P
9	Nov. 8, 1956	U	7	0.92	0.08	1.66	1.62	12.3	−3.0	10.9	2.7	P
10	Nov. 8, 1956	U	2	1.11	0.28	1.66	1.82	11.0	−4.2	15.5	3.4	P
11	Nov. 9, 1956	U	5	1.32	0.16	1.80	1.95	10.5	−3.2	16.7	3.0	P
12	Nov. 10, 1956	U	6	2.49	0.30	3.00	3.20	7.4	−5.0	31.6	3.7	S
13[a]	Nov. 12, 1956	U	11	3.03	0.29	3.49	3.93	7.5	−5.8	35.4	4.6	S
14[a]	Nov. 16, 1956	U	6	2.48	0.15	2.87	3.06	6.0	−4.2	40.2	4.0	S
15	Nov. 16, 1956	U	7	0.63	0.14	2.06	1.66	15.2	−3.0	6.3	2.4	P
16	Nov. 17, 1956	U	8	1.39	0.24	2.04	2.04	9.6	−4.4	15.7	2.8	P
17	Nov. 20, 1956	U	5	1.88	0.30	2.54	2.69	10.1	−6.4	20.4	3.3	P
18	Nov. 20, 1956	U	4	1.38	0.06	1.92	2.02	12.4	−6.4	18.1	3.2	P
19	Nov. 21, 1956	U	7	0.98	0.15	2.09	2.11	16.0	−6.7	8.9	2.9	P
20	Dec. 24, 1955	U	4	1.29	0.28	2.13	. . .	11.8	−3.6	12.7	. . .	S
21	Dec. 25, 1955	U	3	1.30	0.30	1.85	. . .	12.4	−3.2	17.8	. . .	S
22	Dec. 28, 1955	U	12	1.72	0.17	2.48	. . .	9.3	−3.8	16.5	. . .	S
23	Jan. 3, 1956	U	6	2.15	0.30	2.63	. . .	8.3	−4.8	28.9	. . .	S
24	Jan. 4, 1956	U	6	2.47	0.36	2.99	. . .	8.4	−5.5	30.5	. . .	S
25	Jan. 11, 1956	U	5	1.41	0.20	1.67	. . .	7.4	−2.7	36.8	. . .	S
26	Oct. 31, 1956	D	5	1.95	0.62	3.20	3.31	10.4	−4.2	17.2	3.1	P
27	Nov. 1, 1956	D	5	1.73	0.63	2.33	2.61	10.0	−3.0	18.5	3.5	P
28	Nov. 2, 1956	D	4	1.27	0.35	1.72	2.17	8.9	−2.8	20.0	5.2	P
29	Nov. 3, 1956	D	7	1.39	0.17	1.83	2.10	8.3	−2.4	20.8	3.7	P
30	Nov. 5, 1956	D	3	2.74	0.12	3.54	3.86	7.6	−3.6	23.4	3.7	P
31	Nov. 6, 1956	D	3	2.33	0.59	2.98	3.25	8.0	−4.6	24.1	3.7	P
32	Nov. 6, 1956	D	4	1.25	0.11	3.08	2.75	13.0	−3.0	7.7	2.5	P
33	Nov. 8, 1956	D	7	0.84	0.21	1.49	1.33	12.3	−3.0	11.3	2.3	P
34	Nov. 9, 1956	D	4	1.41	0.14	2.02	2.01	10.0	−3.9	17.2	2.8	P
35	Nov. 16, 1956	D	3	0.50	0.19	1.63	1.32	15.2	−4.0	6.3	2.4	P
36	Nov. 22, 1956	D	5	0.93	0.19	2.00	2.04	17.6	−7.0	8.7	2.8	P
37	Nov. 24, 1956	D	7	0.96	0.30	1.48	1.63	11.3	−4.8	14.3	3.3	P
38	Nov. 26, 1956	D	7	0.91	0.11	1.50	1.71	15.2	−6.0	12.8	3.4	P

[a] These tests were performed by Lyle Hansen of SIPRE.

placed in tightly sealed glass containers and allowed to melt. The density of the resulting solution was measured, using hydrometer floats from a salinity kit manufactured by G. M. Manufacturing Co., New York 12, N. Y. All values were corrected to 15°C, using a table supplied by the manufacturer. The temperature of the beam was measured at two or three levels using Weston dial thermometers inserted into drilled holes. The average temperature of the ice sheet was then determined by using both the results of the dial thermometer measurements and temperatures measured by a series of thermocouples frozen into the ice sheet at 10-cm vertical intervals. Typical temperature and salinity profiles during the period of testing are shown by *Anderson* and *Weeks* [1958, Fig 8].

The flexural strength is computed from

$$\sigma = 6PL/wh^2 \tag{1}$$

where P is the force applied to the end of the ice beam at failure; L the distance from the point of application of the force to the point of breakage; w the average width of the ice beam, and h the average thickness of the ice sheet. The results of these tests are presented in Table 1, and σ is plotted against average ice salinity and ice temperature in Figure 1. Each point is the average of all the tests on a given sheet. The push-down tests are identified in the legend. The remainder are pull-ups.

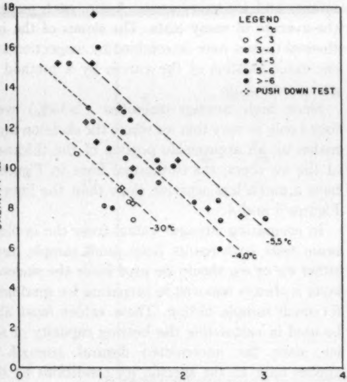

FIG. 1 – Plot of experimental values for flexural strength of sea ice versus salinity at various temperatures, not allowing for the skeleton layer

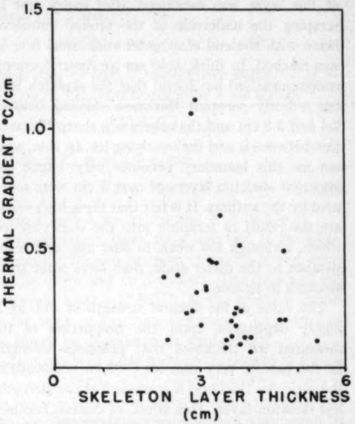

FIG. 2 – Plot of skeleton-layer thickness versus thermal gradient across the ice sheet

The above formula must be considered as only approximate as applied to sea ice. First, the properties of sea ice vary considerably with depth. A variable section modulus should be used in more accurate work. Secondly, the stress concentration at the butt end of the cantilever has been neglected. This permits our work to be compared directly with that of previous investigators.

The study was undertaken to identify the controlling factors in sea-ice properties and thus relative strengths are studied.

It is surprising that the pull-ups and push-downs give essentially the same results. The strength of the beam is determined primarily by the strength of the extreme fiber that is in tension. In push-downs this is the cold upper part of the sheet; for pull-ups it is the warm, weak underside. However, we show [*Anderson* and *Weeks*, 1958] that the bottom and top are the weaker parts of the ice and the maximum strength exists somewhat above the center of the sheet. The low strength of the top is due to the extremely high salinity which only persists to a very small depth.

At the lower surface of the growing ice sheet there is a strengthless layer of unconnected vertical ice plates which has been referred to by Assur as the skeleton layer [*Butkovich*, 1956]. The thickness of this layer was measured after every test by scraping the underside of the broken cantilever beam with the end of a meter stick until firm ice was reached. In thick, cold sea ice Assur (personal communication) has found that the skeleton layer has a fairly constant thickness varying between 2.4 and 2.8 cm and that there is a sharp demarcation between it and the overlying ice. In thin, weak sea ice this boundary becomes very vague and apparent skeleton layers of over 5 cm were measured by the authors. It is felt that these high values are the result of scraping into the overlying ice, which, although too weak to offer appreciable resistance to the meter stick, does have some small strength in tension.

The value of the flexural strength of thin ice is highly dependent upon the proportion of the measured ice thickness that possesses strength. In the case of very thin ice (<3 cm), essentially the entire ice thickness is composed of the strengthless skeleton layer. This effect, of course, becomes lessened as the ice sheet grows since the skeleton layer remains roughly constant. A number of attempts have been made to relate apparent variations in the skeleton layer to other properties. Figure 2 shows skeleton layer thickness plotted against the thermal gradient in the ice sheet. At the present, however, no definite empirical relation has been established. A theoretical relation has been derived [*Anderson* and *Weeks*, 1958].

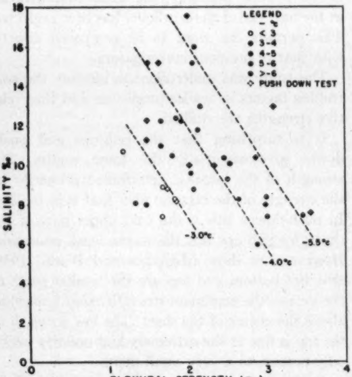

FIG. 3 – Plot of experimental values for flexural strength, assuming a constant 2.8-cm skeleton layer

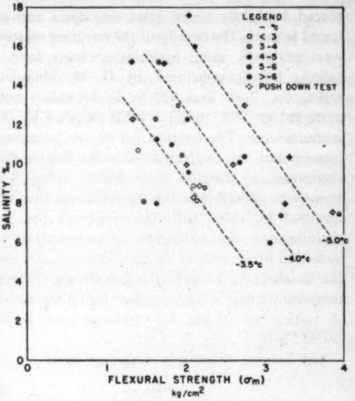

FIG. 4 – Plot of experimental values for flexural strength, using the measured skeleton layer

Therefore two other strength values were calculated: σ_K using for h in (1) the measured ice thickness minus 2.8 cm (assuming a constant value for the skeleton layer) and σ_M using the measured ice thickness minus the measured value of the skeleton layer. Figures 3 and 4 show the flexural strengths, σ_K and σ_M, plotted against average ice salinity and ice temperature. Again, each point is the average of many tests. The slopes of the isothermal curves were determined by inspection and the exact location of the curves by a method of group averaging.

Since high average salinities (>14‰) were found only in very thin ice where the skeleton layer makes up an appreciable portion of the thickness of the ice sheet, the isothermal lines in Figure 1 have a much less negative slope than the lines in Figures 3 and 4.

In comparing strength values from the in-place beam tests with results from small sample tests, either σ_K or σ_M should be used since the skeleton layer is always removed in preparing ice specimens for small sample testing. These values must also be used in calculating the bearing capacity of sea ice, since the uncorrected flexural strength σ applies only to the specific ice conditions at the time of testing, that is, portion of the ice sheet that is skeleton layer.

Young's modulus—For the measurement of Young's modulus on in-place samples of young sea ice, a semi-infinite beam test developed by A. Assur of SIPRE was used. The test procedure is as follows: a 30-cm × 16-m semi-infinite ice beam is cut in the ice sheet. A force is then applied to the free end of the beam causing the beam to break at a distance L from the position of the applied force. The process is then repeated at the new end of the beam. After a number of segments are broken off, the average length of each segment, the thickness of the ice and skeleton layer, and its salinity and temperature profiles are measured.

It can be shown [*Hetényi*, 1946] that for a semi-infinite beam on an elastic foundation

$$M = -(P/\lambda)\, e^{-\lambda l} \sin \lambda l \qquad (2)$$

where M is the bending moment, P the vertical force applied to the end of the beam, l any distance from the end of the beam, and λ the characteristic of the system defined as

$$\lambda = \sqrt[4]{wK/4EI} \qquad (3)$$

where w is the width of the beam, K the foundation modulus (in this case equal to the density of sea water of $\sim 32‰$ salinity at its freezing point, which is $\sim$ 1.0 g/cm³); E is Young's modulus (the Young's modulus determined by this test is definitely not a reversible process where the sample returns to its initial dimension after testing); and I is the moment of inertia $wh^3/12$, where h is the thickness of the beam. This is only approximate since the beam is not homogeneous throughout its thickness. This semi-infinite beam will break at the position where the bending moment M is at a maximum. Therefore

$$dM/dl = -Pe^{-\lambda l} (\cos \lambda l - \sin \lambda l) \qquad (4)$$

which goes to zero at consecutive values of $\lambda l = \pi/4, 5\pi/4$, etc. Substituting for λ we obtain

$$\sqrt[4]{3K/E h^3} = \pi/4l \qquad (5)$$

But since $K = \cong 1.0$ g/cm³

$$E = 7.88\, L^4/h^3 \qquad (6)$$

where L and h are in cm and E is in g/cm².

In performing these tests care had to be taken to prevent friction between the sides of the semi-infinite beam and the ice sheet. The length of the beam was kept $>(1.5\pi)/\lambda$. If the effective length of the beam is less than this value, the beam can no longer be considered as semi-infinite.

The results of these tests are presented in Figure 5. A large scatter in the values is evident. There is no obvious relation between Young's modulus and the ice temperature and salinity. This result is rather surprising since other properties of sea ice are definitely a function of the brine content. The lack of a relation between these properties is obviously caused by the large scatter in the experimental values and insufficient data. Owing to the nature of the test procedure, it is difficult to determine the values of E_K or E_M (the subscripts have the same meaning as in the preceding section) with accuracy, since Young's modulus is inversely proportional to the cube of the effective thickness

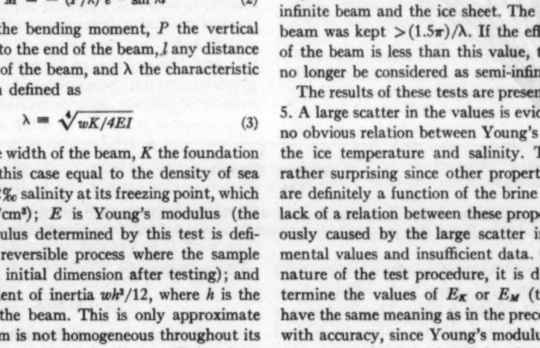

FIG. 5 – Plot of Young's modulus as determined from semi-infinite beam tests

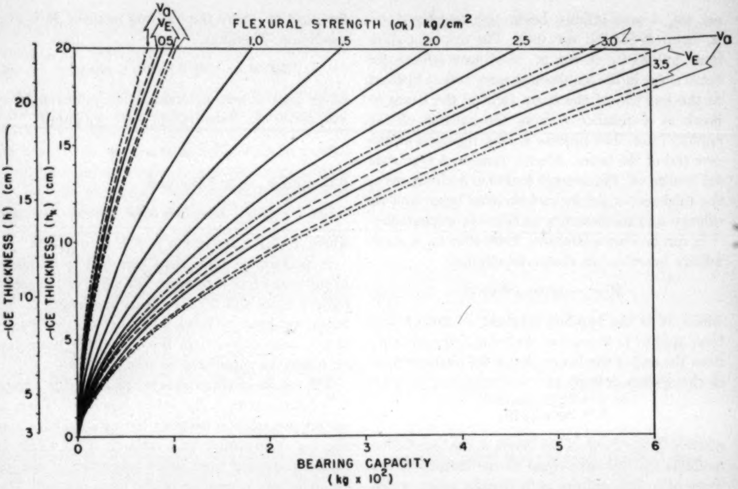

FIG. 6 – Curves showing relationship between bearing strength of a sea-ice sheet and thickness at various values of flexural strength and showing the effect of changing the load radius and changing Young's modulus

of the ice sheet, the value of which, as discussed earlier, depends on an exact measurement of the thickness of the skeleton layer. There is however general agreement between the values for E_K and E_M which average 3570 and 3800 kg/cm² and values determined graphically from the slopes of small sample stress-strain curves by *Butkovich* [1956] on much colder ice. His values varied from 4520 to 10,225 kg/cm² in the temperature range of −4.9 to −18° C.

Bearing capacity—It is interesting to use the experimentally determined values of σ_K and E_K to calculate the ice thickness required to support a walking man and other light loads. This can be done using an analysis developed by *Hertz* [1884] and *Wyman* [1950]. Considering the sheet of thin ice as an infinite isotropic elastic plate resting on an elastic foundation, the force P necessary to cause the first crack is given by

$$P = \frac{\pi \sigma_K b h^2}{3(l + \gamma) kei'b} \tag{7}$$

where γ is Poisson's ratio, $kei'b = (0.6159 - \ln b)(b/2) + \pi b^3/64 + \cdots$ [*McLachlan*, 1941] and $b = a/l_1$ where a is the radius of the circular loading and l_1 is the so-called radius of relative stiffness defined by

$$l_1 = \sqrt[4]{D/K} \tag{8}$$

where K is the foundation modulus and D the flexural rigidity

$$D = E_K h^3/12(1 - \gamma^2) \tag{9}$$

Figure 6 shows the bearing capacity at the first crack plotted against the measured ice thickness h, the effective ice thickness h_K, and the flexural strength σ_K. The values used in calculating these curves are E_K = 3570 kg/cm², a = 15 cm, γ = 0.36, and $K = 10^{-3}$ kg/cm³. The change in the position of the σ_K = 0.5 and 3.5 kg/cm² curves are shown for the values of E_K = 1000 and 8000 kg/cm² (the maximum variation in the measured values) and a = 7.5 and 22.5 cm. As can be seen there is less variation (V_E) in the bearing capacity from a reasonable change in magnitude of E_K than from a reasonable change V_a in a. Therefore even though the Young's modulus tests discussed earlier in this paper did not give a precise determination of E_K, the measured values can be used to calculate the bearing capacity of an ice sheet without introducing an appreciable error.

It is interesting to compare the calculated bearing strengths with observations made during the Thule freeze-up. One of the authors (DLA) was trapped on the off-shore side of a newly frozen lead of a width of ~15 m. As he crossed the lead, using a rapid shuffle, an extreme deflection was noted in the ice sheet and a series of large waves was observed in the ice. When he paused to study the deflection dish around him, a soft crackling sound and a rapid sagging were noted. The ice in the center of the lead was 8 cm thick. Two days later the authors repeatedly crossed over ice areas of 10 cm in thickness, and, although a noticeable deflection was observed, there was no evidence of breakthrough even after jumping on the ice. The weights of the persons in these instances was ~90 kg and σ_K was estimated to be ≤ 1.5 kg/cm^2. From Figure 6 it can be seen that when the ice thickness was 8 cm the ice was loaded far beyond the first crack. Upon stopping, the man probably would have broken through the ice in a short period of time. With 10 cm of ice, however, even though the ice sheet was loaded slightly beyond the first crack, it was able to support the load for an appreciable length of time without noticeable signs of failure. This conclusion is in agreement with studies of A. Assur (personal communication), who has shown by comparing field tests with theoretical computations that ice sheets are capable of supporting a large 'super load' beyond the force necessary to form the first crack.

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The Effects of Entrapped Gases on the Hydraulic Characteristics of Porous Media

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Abstract—Investigation of the hydraulic characteristics of prepared porous media indicate that a ten per cent increase in air content of media voids is capable of producing a 15 pct reduction in 'effective porosity,' a 35 pct decrease in permeability, and about 50 pct reduction in hydraulic dispersion. The location of bubbles in large or small pores affects the uniformity of pore sizes and determines the amount of water saturated void volume which is isolated by air bubbles. The shape of the chloride tracer 'breakthrough' curve is greatly modified by changes in uniformity of pore size. An appreciation of the effects of gas accumulation is essential to a proper interpretation of the hydraulic behavior of natural formations.

A thorough engineering appraisal of the hydraulic characteristics of a particular porous medium is essential to an intelligent interpretation of the probable performance of this material in the transmission of ground water in situ. In particular, the ground-water geologist or engineer should determine the porosity and permeability for the medium under conditions which are likely to be obtained in practice. He should also be aware of the variable nature of the hydraulic characteristics of the medium as a consequence of changes in climatic or geologic conditions or variations in water quality.

Many factors govern the hydraulic properties of natural aquifer materials. The physical characteristics of the water are particularly important and their effects are well understood. The characteristics of the medium; its particle size, shape, and distribution, its chemical composition; and the geologic structure of the aquifer in which it is deposited are likewise important and generally appreciated by both engineers and geologists. If, however, in addition to solid and liquid phases, a gaseous phase is present in the system an interpretation of the hydraulic behavior of the medium is somewhat complicated. Often the gaseous phase may be justifiably ignored with no appreciable error in result. But, occasionally the influence of accumulated gases may be great, as for example, in the case of artificial ground-water recharge; and cannot be neglected.

It is the particular objective of this paper to explore the problem of gas accumulation in porous media and to illustrate by the presentation of experimental results the effects of this phenomenon on the hydraulic characteristics of the medium. Particular attention is given to media porosity and permeability and hydraulic dispersion of transmitted water.

Sources of entrapped gases—Some of the more significant influences on the hydraulic performance of a porous medium are those occasioned by the entrapment of gases in interstitial cavities. Such gas accumulations may originate by liberation of any or all of the components of the atmosphere which were originally dissolved in and in equilibrium with natural ground-water recharge. Temperature increases during underground percolation with the resultant reduction in equilibrium saturation can bring about the evolution of dissolved gas. Similarly, pressure differences, especially tensions developed in the capillary fringe near the ground-water table or vertical percolation of water through strata of varying permeability can cause the evolution of dissolved gases.

The products of decomposition of organic sedimentary deposits commonly include such gases as carbon dioxide, methane, and hydrogen sulfide. Evolution of these gases and their eventual migration or displacement into water-transmitting aquifers can also lead to significant gas accumulations in media voids.

Natural-gas deposits which may be displaced by flooding operations or which may be intercepted by natural faulting or by drilling operations can contribute to gas accumulation in adjacent water-bearing strata.

Currently, attention has been directed to methods of artificial ground water recharge such as direct injection [*McGauhey* and *Krone*, 1954] and surface spreading [*Greenberg*, 1953; *Orlob* and *Butler*, 1955]. Waste waters which have been considered for reclamation range from excess surface runoff or irrigation water to diluted domestic sewage. Dissolved organic solids and the bacteria which are required for stabilization may thus be introduced into producing aquifers. Subsequent breakdown of organic matter can result in production of carbon dioxide or other gases of decomposition in excess of the ability of the aquifer to remove them.

Movement of the gaseous phase—The ultimate persistence of accumulated gases in a given location may depend on the capacity of the liquid phase for solution of the gas and the hydraulic forces which develop behind an individual bubble and tend to move it forward through the medium.

If gas is continually supplied through the liquid phase in excess of saturation, an equilibrium between liquid and gas is established and the gas accumulation may remain constant. According to *Wyckoff* and *Botset* [1936] the gaseous phase remains static, that is, the medium is impermeable to the flow of gas, until a so-called 'equilibrium saturation' is attained. In studies by these investigators on four different sands (permeability range 17.8 to 262 Darcy's) the equilibrium saturation was noted to correspond to about 11 to 27 pct gas in the media voids and was found to be roughly proportional to the permeability. Permeabilities associated with equilibrium saturation were termed 'equilibrium permeabilities.'

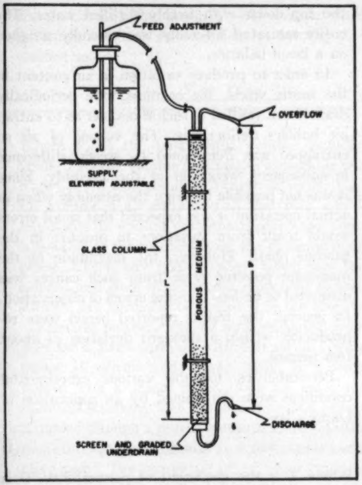

Fig. 1 – Experimental column

Table 1 – *Physical characteristics of porous media*

Size distribution	Parent material						
	Hanford A	Hanford B	Hanford C	Hanford D	Hanford E	Hanford F	Oakley G
mm	pct[a]	pct[a]	pct[a]	pct[a]	pct[a]	pct[a]	pct[a]
<0.05	0	0	1	0	0	0	14
0.05–0.10	0	0	9	24	11	12	15
0.10–0.20	0	3	74	31	33	25	25
0.20–0.30	0	27	16	12	16	18	34
0.30–0.40	0	46	0	22	12	16	5
0.40–0.50	0	20	0	7	20	6	4
0.50–0.60	0	4	0	4	7	7	3
0.60–0.70	0	0	0	0	1	11	0
0.70–0.80	6	0	0	0	0	1	0
0.80–0.90	10	0	0	0	0	4	0
0.90–1.00	30	0	0	0	0	0	0
1.00–1.10	27	0	0	0	0	0	0
1.10–1.20	11	0	0	0	0	0	0
1.20–1.30	5	0	0	0	0	0	0
1.30–1.40	5	0	0	0	0	0	0
1.40–1.50	4	0	0	0	0	0	0
1.50–1.60	2	0	0	0	0	0	0
>1.60	0	0	0	0	0	0	0
Median size, d_{50} mm	1.10	0.40	0.19	0.27	0.23	0.25	0.19
Effective size, d_{10} mm	0.92	0.29	0.14	0.14	0.098	0.08	0.02
Uniformity coefficient = d_{60}/d_{10}	1.28	1.43	1.60	2.28	3.06	3.88	11.2

[a] Per cent by weight.

The Wyckoff and Botset investigations were concerned primarily with high gas-to-liquid ratios such as might result during flooding operations for gas recovery in an oil field. Contrariwise, the problem of greatest concern to the geohydrologist it that of low gas-to-liquid ratios, particularly those in which the gaseous phase is static. The investigations discussed in this paper deal with the latter problem, that of gas accumulations in the range of 0 to 25 pct of the total void volume.

Experimental procedure—The program of investigation was designed to illustrate as simply as practicable the effect of gas accumulation on (1) the effective porosity of the medium, (2) the permeability of the medium to water, and (3) the hydraulic dispersion of water passing through the system. Apparatus for the studies was simple in design, consisting of a cylindrical glass column about one meter in length and about 32 mm in diameter fitted with an underdrain of fine screen, a discharge tube of variable diameter, an overflow for the regulation of hydraulic gradient, and supply reservoirs. The media column was so designed that when in operation the fluid pressure was nearly uniform along the axis of the column, equivalent to about two inches of water. The physical arrangement of equipment is shown in Figure 1.

The media used in the experiments were obtained by sieving, from the same parent stock, fractions which were as uniform as possible and very nearly of geometrically normal size distribution. Individual grains were slightly rounded with a maximum length to width ratio of about 1.5:1.0 and were composed largely of quartz and feldspars. In order to study the effect of non-uniformity of size on the hydraulic characteristics of the media several samples were prepared by mixing fractions of uniform materials to obtain the desired size distribution. A few investigations were carried out on a disturbed sample of a highly permeable agricultural soil; Oakley sand. Table 1 summarizes the characteristics of the various materials employed in the experiments.

Columns were packed by pouring the media into the column at a constant rate while the assembly was continuously vibrated. Care was taken to minimize stratification or sorting of individual grains during packing. When the columns were assembled the absolute porosity was determined by gravimetric methods using column volume, media weight, and a specific gravity of 2.69. Subsequently, columns were subject to a vacuum of approximately 30 inches of mercury and saturated from the top down with freshly distilled water. The entire saturated assembly was carefully weighed on a beam balance.

In order to produce variation in air content in the media voids, the columns were periodically drained and refilled in such a manner as to entrap air bubbles deliberately. The volume of air so entrapped was determined by weight difference in subsequent weighings of the assembly. Since it was not possible to weigh the assembly when in actual operation it was expected that small errors would result from variations in pressure in the gaseous phase. However, the magnitude of the maximum possible error from such causes was estimated to be less than the errors of observation. In general, the results reported herein were reproducible within a standard deviation of about two percent.

Permeabilities for the various experimental conditions were determined by an application of Darcy's law

$$K = Q/As \tag{1}$$

Where K is the coefficient of permeability, Q is the discharge through a cross sectional area A, and s is the hydraulic gradient imposed on the system.

A dimensional consideration of Darcy's law relates K to the properties of the fluid and solid phases through the equation

$$K = \text{Const.}\, d^2/\nu \tag{2}$$

Where d is a characteristic dimension of the medium, often taken as an effective grain size, and ν is the kinematic viscosity of the fluid. The numerator is usually designated as simply permeability k in darcys and is a function only of the solid phase of the porous media system. While Wyckoff and Botset asserted that Darcy's law is inadequate to describe the dynamic behavior of non-homogeneous fluid mixtures it has been well established in previous studies on porous media, by *Day* and *Luthin* [1953] and *Orlob* and *Butler* [1956], that the fundamental relation is applicable to water movement as long as the liquid phase remains continuous through the medium. Columns of uniform porous media have been successfully operated with as little as 25 pct of the void space occupied by water which flowed over grain surfaces as a laminar film [*Orlob* and *Krone*, 1956].

In order to apply Darcy's law to the problem of estimating velocity of water movement through a liquid – gas – solid system it is essential to evaluate the so-called effective porosity of the medium, the fraction of the absolute void volume which actually transmits water. Effective porosity f_e is defined as

$$f_e = \frac{V_e}{V_t} = \frac{V_v - V_a - V_b}{V_t} \tag{3}$$

Where V_t is the bulk-media volume including voids, V_e is the volume of readily displaceable pore water, V_v is the absolute volume of voids, V_a is the volume of air entrapped in the voids, and V_b represents the volume of stagnant pore water which is isolated in the medium from the dynamic liquid phase. Chemically bound water, which was considered negligible in the media employed in these studies, can normally be included in the term V_b.

Effective porosity can be independently evaluated for a given medium with the aid of a water tracer [*Kaufman* and *Orlob*, 1956]. If a water tagged with a tracer which does not enter into chemical reactions with the liquid or solid phases, is passed through a porous medium a characteristic breakthrough curve results at a downstream sampling point. The concentration of tracer gradually increases from zero to the full initial concentration over some time (or distance or volume displacement) which is characteristic of the physical and hydraulic properties of the particular media. All breakthrough curves reported in this paper were obtained using chloride ion as a tracer. Previous experience has shown that chloride when used in low concentrations possesses most of the attributes of the ideal water tracer. A typical tracer curve is shown in Figure 2.

If the tracer curve is normalized so that the ordinate is expressed as a ratio of sample concentration to initial concentration and the abscissa is given as a ratio of volume displaced to total media volume then the effective porosity is represented by the area over the curve as

$$f_e = \int_0^\infty \left(1 - \frac{C}{C_0}\right) d\left(\frac{V}{V_t}\right) \tag{4}$$

Thus the tracer curve serves as a means of estimating the fraction of the pore volume which participates actively in the flow.

In a medium which does not react chemically or biologically with the tracer the shape of the tracer curve is dictated only by the geometry of the passages which transmit the liquid carrying the tracer. If statistical isotropy is obtained in the assemblage of media pores, the dispersion of the tracer front as it progresses through the medium is brought about by a disordered series of movements superimposed on the basic flow regime. Such a pattern as would theoretically result from a statistical treatment by the random-walk technique or a solution of Fick's second law of diffusion [*Rifai*, 1956] is conveniently described by the equation

$$\frac{C}{C_0} = \tfrac{1}{2}\left[1 - \operatorname{erf}\frac{L - \bar{v}t}{2\sqrt{Dt}}\right] \tag{5}$$

Where L is the distance between the point of tracer entrance and the sampling point, $\bar{v}$ is the average velocity of water movement through the media pores, and t represents the time of travel of a particular element of fluid to the sampling point. The coefficient of dispersion D defines the shape of the tracer curve on a dimensionless plot of C/C_0 against t/t_0 where t_o is taken as the time for $C/C_0 = 0.5$ to arrive at the sampling point.

It was observed by *Rifai* [1956] and also *Orlob* and *Krone* [1956] that the coefficient of dispersion was directly proportional to the velocity of flow

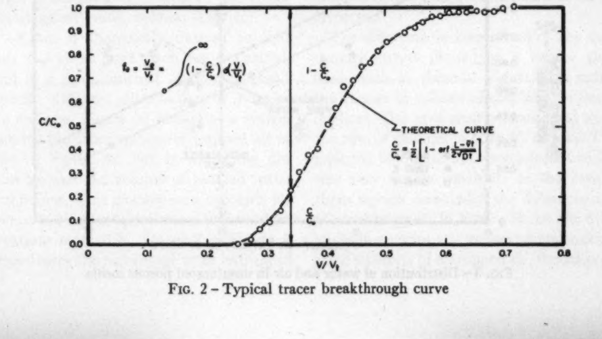

FIG. 2 – Typical tracer breakthrough curve

$\bar{v}$. The latter investigators pointed out, however, that dispersion, *per se*, is independent of velocity and that the ratio of D to $\bar{v}$ is a constant for a given porous medium system. *Orcutt* and coworkers [1957], letting $D\bar{v} = D_m$, the socalled medium dispersion constant, have rewritten (5) in the form

$$\frac{C}{C_0} = \frac{1}{2}\left[1 - \operatorname{erf}\frac{1 - \dfrac{V}{V_e}}{2\sqrt{\left(\dfrac{D_m}{L}\right)\left(\dfrac{V}{V_e}\right)}}\right] \tag{6}$$

Where V/V_e is the ratio of the volume of water displaced to the hydraulically effective void volume, L is the distance of flow, and D_m is a constant which characterizes the hydraulic dispersion properties of the medium.

Effective porosity and air accumulation—A comparison of the absolute void volume of a porous medium V_v with the displaceable water volume V_e for a known amount of air entrapped V_a permits an estimation of the amount of water in the system which does not participate in the flow V_b. When the medium is completely saturated the value of V_b should be minimal; it was, in fact, observed to be virtually zero for the various materials used in these studies. For example, the effective porosity for saturated sand E was estimated from the area ahead of the chloride breakthrough curve to be 0.401. A determination based on gravimetric techniques using a specific gravity of 2.69 (determined by water displacement at 20°C) gave an absolute porosity of 0.402. The close agreement between these two techniques is satisfactory evidence that the column was completely saturated and that a negligible amount of stagnant water was contained in the system, that is, $V_e = V_v$ when the medium was saturated.

Entrapment of a small amount of air in the pore spaces of the medium produced a volume discrepancy which could only be accounted for by assuming that some of the water contained in the voids was actually trapped by the air bubbles in such a way that it was isolated from the main stream of flow and was not displaced during the passage of the chloride tracer. As might be expected the volume of water so isolated varied considerably with each individual set up, ranging up to about 5 pct and averaging about 2.5 pct of the total pore volume.

A comparison of displaced volume to the void volume for all of the tests which were conducted with sufficient detail to permit calculation of the required quantities is shown in Figure 3. It is to be noted that no discernible trend in V_b with per cent air entrapment is apparent and that all values fall below the line $V_e/V_v = 1 - V_a/V_v$.

The manner in which a portion of the void volume isolated from the main flow regime is illustrated schematically in Figure 4. A typical section taken parallel to the axis of flow in a column of heterogeneous sand can be expected to appear somewhat as shown in Figure 4a. Pores of varying size are distributed through the medium in a somewhat random manner and occasional pockets of small grains may exist.

When air is admitted to the larger, more easily drained pore spaces, small bubbles are formed

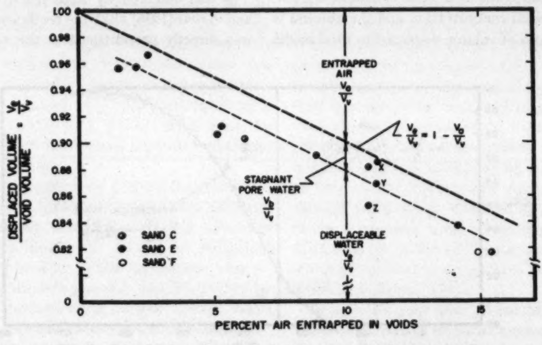

Fig. 3 – Distribution of water and air in unsaturated porous media

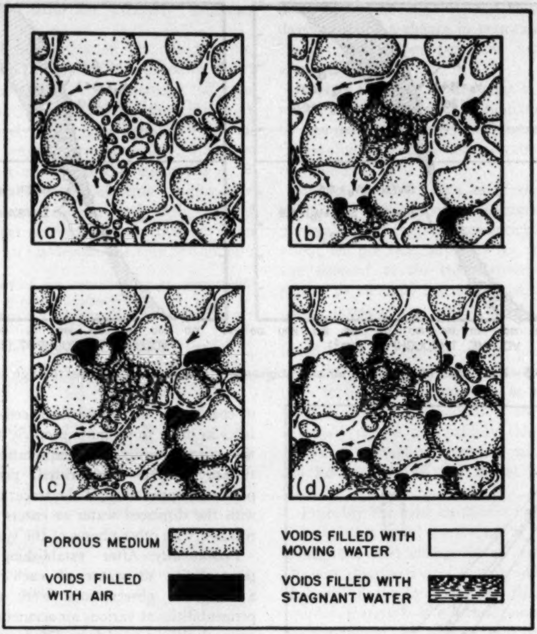
(a)
(b)
(c)
(d)
POROUS MEDIUM
VOIDS FILLED WITH AIR
VOIDS FILLED WITH MOVING WATER
VOIDS FILLED WITH STAGNANT WATER

Fig. 4 – Distribution of air and water in a porous medium; (a) voids saturated with water; (b) five per cent air in voids; (c) ten per cent air in voids (large voids only); (d) ten per cent air in voids (all void sizes affected)

Upon resumption of flow (Fig. 4b) these bubbles are forced into the small crevices leading out of the pore spaces thus sealing off a portion of the water filled medium from active participation in the flow. Further increases in air volume entrapped in the larger pores produce comparatively minor changes in stagnant water volume (Fig. 4c).

If the column is thoroughly drained so that small pores as well as large pores are evacuated, entrapment of a given amount of air may result in an entirely different distribution of bubbles within the medium. Figure 4d illustrates a system which contains the same volume of trapped air as that shown in Figure 4c, but in which the distribution of air and the volume of isolated water are quite different. This phenomenon accounts for the difference in stagnant pore water indicated for the observations marked X, Y, and Z in Figure 3. In these three cases the percentage of air entrapped ranged only between 10.9 and 11.2 pct while the stagnant water was estimated to vary from 0.5 to 4.0 pct of the total pore volume. As will be demonstrated later these differences produce a negligible change in the permeability of the medium but have considerable influence on hydraulic dispersion.

The difference in area ahead of any two breakthrough curves plotted on a volume throughput basis, such as those in Figure 5, is indicative of the change in volume of displaceable liquid in the medium. This area must be considered as reflecting the sum of changes in both V_a and V_b. The curves reported in Figure 5a, were selected such that V_b was very nearly constant; so the area between them reports essentially the difference in volume of air entrapped. In Figure 5b, on the other hand, while the curves still represent approximately the same amounts of entrapped air, the stagnant-water

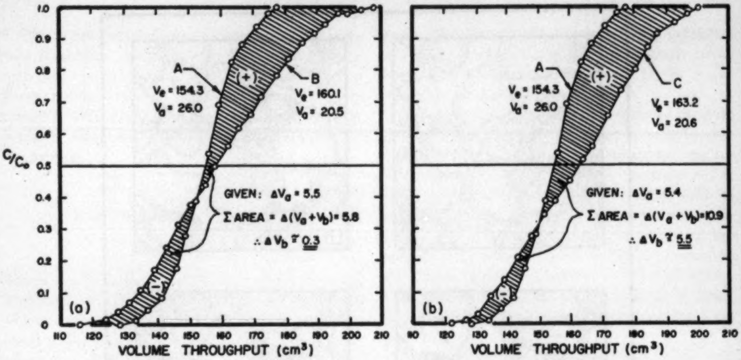

FIG. 5 – Estimation of entrapped air and stagnant water from chloride breakthrough curves

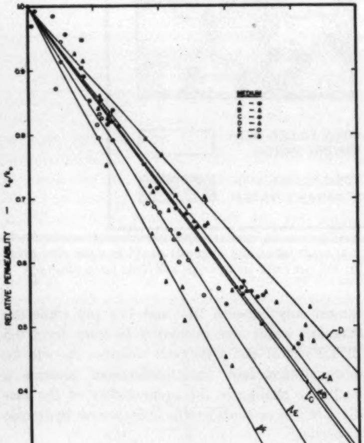

FIG. 6 – The effect of air entrapment on the permeability of porous media

volume is no longer equal in the two cases. The area between the curves in this latter case represents the sum of differences in air and stagnant water.

It is apparent that if tracer curves are to be used in water-flooding operations in an oil field, for example, care must be exercised in interpretation of changes in shape and displacement characteristics in order to estimate properly the changes in the porous medium. Interpretation is unquestionably further complicated, perhaps to the point of impossibility, if the tracer does not move with the displaced water or enters into chemical reaction with other phases of the system.

Permeability—After establishing the initial permeability to water of each test medium a series of observations were made of the permeabilities at various air accumulations. Initial permeabilities ranged from 478 darcys for medium A to 8.7 darcys for medium F. Air was accumulated in the various media in volumes sufficient to reduce the permeability to less than one-half of the original value. The results of these tests are summarized graphically in Figure 6.

In each of the six cases reported, the relationship between permeability and air accumulation was essentially linear, taking the general form

$$k_a/k_0 = 1 - m(V_a/V_v) \qquad (7)$$

in which V_a/V_v is the fraction of the original void volume occupied by air, k_a/k_0 is the ratio of the permeability of a partially saturated medium to the permeability of the same medium fully saturated, and C is a coefficient.

The extreme sensitivity of permeability to gas accumulation in the pore spaces of porous media is readily apparent upon inspection of the data in Figure 6. The values of m taken from the graphical lines of best fit were found to range from 0.23 to 0.39, that is, a ten per cent air accumulation caused a permeability reduction generally exceeding 23 pct.

There is a strong indication from the data presented for media D, E, and F that the permeability change increases with non-uniformity of grain sizes. Uniformity coefficients for these materials were, respectively, 2.28, 3.06, and 3.88 while the corresponding values of *m* were 0.23, 0.33, and 0.39. The most uniform media, specimens A, B, and C with uniformity coeficients ranging from 1.28 to 1.60, showed comparatively little variation in the coefficient *m*. A cursory examination of the characteristics of Oakley sand, a very non-uniform material with an initial permeability of about 1.6 darcys showed a change in permeability of about 39 pct for a ten per cent increase in air accumulation.

A minor tendency for the value of *m* to decrease with an increase in size of medium is also suggested by the data but insufficient information was obtained for conclusive interpretation of such a relationship.

Inspection of the data of *Wyckoff* and *Botset* [1936], although it does not document adequately permeability changes for gas accumulations below about ten per cent, supports the conclusion that the segment of the curve covering this range should be virtually a straight line. If the data of these investigators which give permeabilities greater than the equilibrium permeability are fitted with an equation of the form of (7), the coefficient *m* is observed to range from about 0.26 to 0.32. An increase in *m* with increased heterogeneity of the medium is also suggested. A summary of the permeability characteristics for media A through G together with four media studied by Wyckoff and Botset is presented in Table 2.

Probably the most significant factor influencing the variation in *m*, the change in relative permeability per unit change in air accumulation, is the size distribution of water-transmitting pores throughout the medium. In randomly packed uniform materials of constant porosity it is a fair approximation to assume that pores also are nearly uniform in size and that comparatively little water will reside in dead end or non-trans-

TABLE 2 – *Effect of gas accumulation on permeability of porous media to water*

Medium	Size[b]	Unif. Coef.	Absolute porosity *f*	Permeability[c]	Gas	Coefficient *m*, Eq. 7
				darcys		
A	1.1	1.28	0.408	478	Air	0.280
B	0.4	1.43	0.421	68.4	Air	0.275
C	0.19	1.60	0.444	17.1	Air	0.267
D	0.27	2.28	0.407	19.6	Air	0.230
E	0.23	3.06	0.401	13.0	Air	0.327
F	0.25	3.88	0.347	8.7	Air	0.390
G	0.19	11.2	0.407	1.6	Air	0.384
Unconsolidated sand[a]	70–120 mesh	low	....	17.8	CO_2	0.295
Ottawa sand[a]	40–50 mesh	low	...	53.6	CO_2	0.290
Ottawa sand[a]	20–30 mesh	low	0.354	262	CO_2	0.260
Heterogeneous sand[a]	...	high	0.278	44.3	CO_2	0.315

[a] After *Wyckoff* and *Botset* [1936].

[b] Median size d_{50} in millimeters, except as noted.

[c] Initial permeability to water at 100 pct saturation.

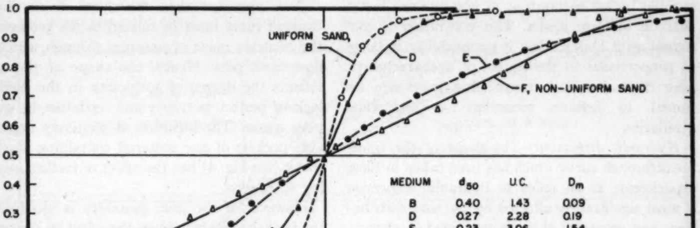

FIG. 7 – Effect of uniformity of grain size on hydraulic dispersion in saturated porous media

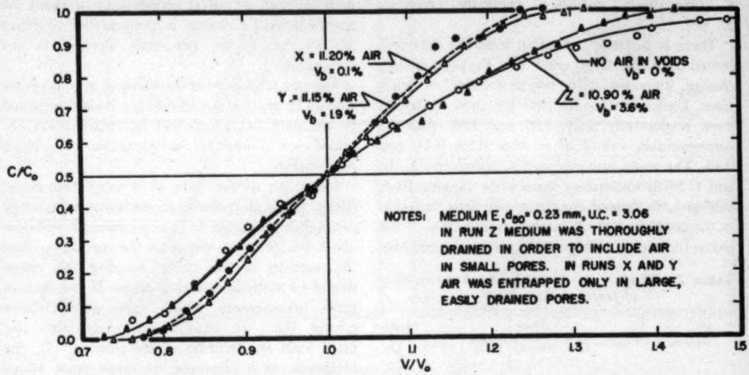

FIG. 8 – The effect of hydraulic dispersion of distribution of air in pore spaces of a porous medium

mitting pores. Accumulation of air in such a medium results in a fairly uniform alteration in pore geometry through the entire pore-size spectrum. The result, so far as permeability is concerned, appears to be a nearly linear reduction in permeability at a rate of about 26 pct per ten per cent change in air accumulation up to about 20 pct total air accumulation.

If, in non-uniform granular materials, bubbles tend to accumulate chiefly in the larger pore spaces there results a disproportionate change in the geometry of pore spaces. Hence, as can be seen from Figure 6, permeability is more severely restricted by air entrapment in non-uniform media than in uniform media. This conclusion is consistent with Darcy's law if permeability is taken as proportional to the square of a characteristic pore dimension and transmitting pores are assumed to behave somewhat as individual capillaries.

Hydraulic dispersion—The shape of the tracer breakthrough curve which has been taken in these experiments as an index to hydraulic dispersion is most significantly affected by the size, distribution, and geometry of pores contained in a representative unit volume of porous medium. Owing to the inherent complexities of porous-media systems, dependable methods of defining these parameters have not as yet been devised so it must suffice to relate dispersion characteristics to grain size and distribution and the effective porosity of the medium.

Comparison of many dispersion curves from columns of sand from the same parent stock showed that the size of medium *per se* had no influence on the shape of the curve. However, as the uniformity coefficient was increased the degree of dispersion, as indicated by the slope of the breakthrough curve, rapidly increased. Figure 7 shows the effect of non-uniformity on the shape of breakthrough curves for saturated sands of the same parent materials. The medium dispersion constant was noted to vary from 0.09 for a very uniform sand (uniformity coefficient = 1.43) to 2.79 for a sand with a comparatively wide range of grain sizes (uniformity coefficient = 3.88).

It is apparent that the shape of the breakthrough curve must be related to the geometry of the intricate maze of passages through which the flow must pass. Hence, the shape of the curve reflects the degree of tortuosity in the medium, lack of perfect isotropy, and variation in size of pore spaces. The inclusion of relatively impermeable pockets of fine material containing stagnant water (see Fig. 4) has the effect of further increasing dispersion.

However, if the pore geometry is modified by the inclusion of air bubbles the effect on dispersion is greatly dependent on the location of the bubbles. In Figure 8 are shown four dispersion curves for the same porous medium (sand E). Three of the curves represent tests in which the volumes of entrapped air was substantially the same (between 10.9 and 11.2 pct). The breakthrough curve for fully saturated flow is also shown for comparison.

In the case documented by curve Z, with 10.9

pct air entrapped in the voids, hydraulic dispersion was not greatly different from that produced by the fully saturated medium. This column was prepared for testing by subjecting the medium to draining under a tension of about 750 mm for one-half hour so that upon readmitting water many of the smallest pores probably contained air. The medium dispersion constant D_m for this case was estimated at 1.29 while that for saturated flow was about 1.54.

In cases X and Y with 11.2 and 11.15 pct air entrapped in the voids respectively, the breakthrough curves were much steeper, that is, dispersion was reduced. The medium dispersion constant D_m for these two cases was estimated at 0.72 and 0.71 respectively. Both of these columns were drained and rewetted in such a way that air was trapped primarily in the larger pore openings.

The apparent result of the selective location of air in the larger, more easily drained pores was to make more uniform the total aggregation of pores actually effective in water transmission; hence, the tendency of curves X and Y (Fig. 8) more nearly to approximate the shape produced by the highly uniform sand of Figure 7. For curve Z, on the other hand, each pore, large or small, received a more nearly proportionate amount of air. Such a distribution of air, while it isolated a larger fraction of the displaceable water volume (see point Z, Figure 3), produced a comparatively negligible effect on the distribution of pore sizes, probably translating the whole spectrum slightly in the direction of decreasing size.

When a small amount of air, say less than five per cent of the total void volume, was entrapped in only the larger pores the effect on hydraulic dispersion was not very pronounced. It is quite possible that inclusion of a small amount of air could have decreased the uniformity of pore spaces, thus increasing dispersion. In a few cases studied a slight increase in D_m was noted at low air concentrations. Experiments in this range were not easily duplicated.

Figure 9 summarizes the results of a series of tests performed on medium E, a fairly non-uniform material, in which the air content ranged from 0 to 14.3 pct of the total void volume. In each instance reported in the figure, air was entrapped primarily in the larger, more readily drainable pores.

An abrupt alteration in the shape of the breakthrough curve was apparent when the air content exceeded about five per cent. The steepening of the curves corresponds to a decrease in dispersion or D_m as can be seen from Figure 10 and reflects an increase in uniformity of the medium which is effectively transmitting the fluid. D_m decreased rapidly when the air content was more than 5 per cent, dropping from about 1.2 to less than 0.1 at about 14 pct.

An even more pronounced effect of air entrapment on D_m was noted for medium F (uniformity coefficient = 3.88). D_m dropped from 2.79 for a fully saturated medium to about 0.082 for a medium containing 15.3 pct air in the voids.

It is clear that the extent to which hydraulic dispersion is influenced by air entrapment is dependent on the location of air bubbles in void spaces and also on the structure of the porous medium. In systems where air may enter only the pore spaces; for example, in the practice of intermittent water spreading, it is to be expected that

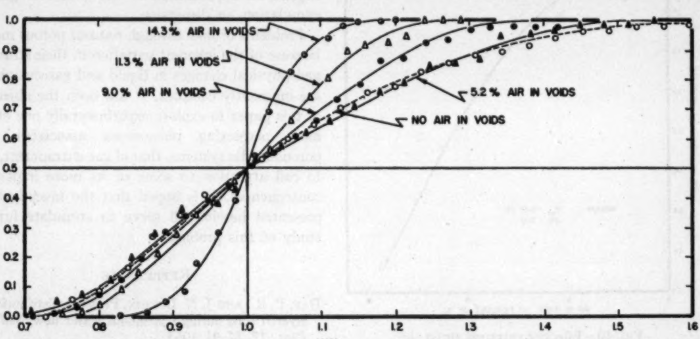

Fig. 9 – The effect of entrapped air on hydraulic dispersion in a porous medium

dispersion will be decreased as air is accumulated. On the other hand if air, or other gases, are liberated uniformly throughout pores of all sizes the effect on dispersion will probably be small. In general, the more nearly uniform is the medium, the less will be the influence of entrapped gas on dispersion. Also, in uniform media the location of gas accumulation, whether in large or small pores, appears to be unimportant.

Discussion—It is evident that comparatively minor modifications in the geometry of a porous medium by inclusion of a static gaseous phase can produce some rather significant changes in the hydraulic characteristics of the medium. These changes and the mechanisms through which they are accomplished have received some attention from soil scientists and physicists in the oil industry but seem to have been little appreciated in published technical literature and reference texts on ground-water hydrology.

A ten per cent accumulation of air in media void spaces may produce as much as 15 pct reduction in effective porosity of comparatively uniform materials such as were used in the studies reported herein. It is reasonable to expect that in more heterogeneous natural media, the isolation of pore volume by entrapped gases would be even more pronounced. Inasmuch as the estimation of velocities of water travel is dependent on porosity, it becomes important to evaluate properly the fraction of the medium volume which actually participates in the flow regime. Variations in time of flow or volume displacement may be, in part, accounted for by changes in effective porosity due to gas accumulations.

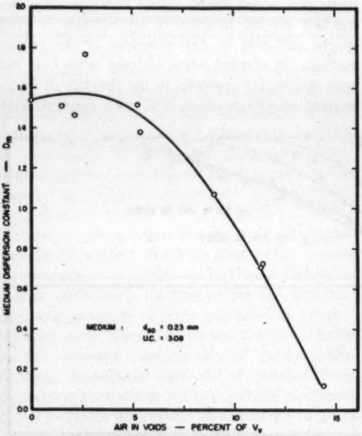

FIG. 10 – Effect of entraped air on the medium dispersion constant D_m

Changes in permeability caused by gas entrapment appear to be particularly important to the practical ground-water geologist or engineer. Variations in temperature and pressure from natural causes may bring about liberation or solution of gases in a natural formation with resultant changes in transmission characteristics. Artificial recharge of ground-water reservoirs by waste surface waters, or even certain industrial or domestic sewages, undoubtedly would induce some alterations in the gas content of an aquifer as a consequence of the bacterial or chemical characteristics of the recharge water. Since the permeability of a porous medium can generally be reduced more than 25 pct by a change in gas content of ten per cent it is apparent that gas entrapment could be an important factor in determining the potential capacity of an underground water supply or the practicality of a water reclamation scheme.

The increasing interest of engineers, geologists, and soil scientists in the mechanics of hydraulic dispersion and the more common use of ground-water tracers dictates a need for a better understanding of factors which control the shape of the dispersion or 'breakthrough' curve. The data presented in this paper show that gas entrapment may drastically alter the shape of the tracer curve. Proper interpretation of successive tracer studies on the same natural aquifer would unquestionably require an appreciation of the effects of gas accumulation on dispersion.

Problems of flow through natural porous media, because of the inherent variation in their structure and physical changes in liquid and gaseous phases are inherently complex. It has been the objective of this paper to explore experimentally one of the more perplexing phenomena associated with porous-media systems, that of gas entrapment, and to call attention to some of its more important consequences. It is hoped that the investigations presented herein will serve to stimulate further study of this problem.

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Ground-Water Studies in New Mexico Using Tritium as a Tracer

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***Abstract*—A new method for ground-water investigations is described which employs tritium as a tracer. Tritium is produced in the atmosphere by cosmic radiation and hydrogen-bomb explosions, the latter causing large peaks in the tritium concentration of rain water. These peaks show up subsequently in underground water. Thus, an 'apparent' age of ground-water samples can be determined, enabling inference as to hydrological quantities such as the rate of flow of aquifers and the size of recharge reservoirs. To demonstrate the feasibility of the method, measurements were made on ground-water samples from New Mexico. Since the tritium content of the samples was extremely low, the tritium was enriched by electrolysis, and its concentration determined by the use of the low-level counting technique.**

Introduction—The problem of establishing sufficient water supplies for industry, agriculture, and domestic usage is rapidly growing more serious and may well become of basic worldwide concern if the present rate of population growth and economic development is maintained.

Conventional hydrologic determinations of the size and recharge of ground-water reservoirs and the properties of aquifers are often inadequate because of the complexity of the phenomena involved. New avenues of approach appear desirable, therefore, to supplement hydrologic studies, especially if thereby certain quantities become measurable which are beyond the reach of conventional techniques. The present paper describes such a method, together with some experimental results obtained by the New Mexico Institute of Mining and Technology. Advantage is taken of the circumstance that hydrogen-bomb tests in recent years have produced considerable quantities of radioactive water, the detection of which allows a determination of the 'apparent' age of the water.

The radioactive water constituent used in this research is tritium, the hydrogen isotope of mass 3, which has a half life of 12.5 years. Tritium is a nearly ideal tracer for ground-water studies because it is a part of the water molecule itself; further, its half life establishes a time scale between 0 and 30 years, which is convenient for the study of most ground-water problems [*Libby*, 1953]. It may be noted also that there is no radiation hazard in the use of tritium, because only small quantities are required with the very sensitive detection devices available, and because the maximum energy of the decay particle is only 18 kev. Thus no special precautions are required.

Tritium follows the flow of water without sufficient selective precipitation or absorption in the water-bearing formation to interfere with its use as a tracer. Tritiated water exchanges to a minor degree with water adsorbed on clay particles, as *Kaufman* and *Orlob* [1956] have demonstrated; the effect of the exchange, in their work, was to give the appearance of slower motion of the tritiated water through clay to the extent of about five per cent.

The work here reported makes use of tritium originating in the atmosphere as a tracer for subsurface waters. This tritium has two principal sources of origin. The first source is natural, inasmuch as tritium is formed by cosmic-ray bombardment of atoms in the upper atmosphere [*Currie* and others, 1956] and possibly also by direct accretion from the Sun [*Craig*, 1956]. Most of this tritium is oxidized and appears at the surface of the Earth in somewhat variable concentrations as a radioactive constituent of rain water. The concentration of tritium produced by natural means and associated with rain at the Earth's surface will depend upon the trajectory and general history of the water vapor involved. Values of the order of one tritium atom in 10^{17} water molecules have been found by Libby and coworkers [*Kaufman* and *Libby*, 1954; *von Buttlar* and *Libby*, 1955].

The second important source of tritium in the atmosphere is the thermonuclear reactions provided by hydrogen-bomb tests. Although the concentration of tritium produced by bomb explosions as observed in rain and surface water will exhibit at first the geographical spottiness characteristic of atmospheric contamination from such sources, the result soon becomes widespread and hemispheric in its extent. Thus the tritium content of surface waters has been raised quite generally by a factor of from 10 to 100.

The first thermonuclear explosion (March 1954)

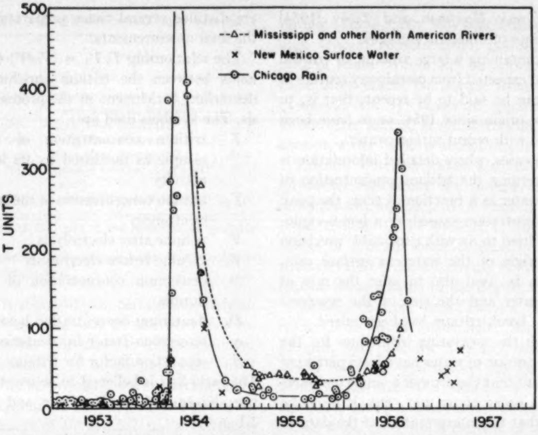

FIG. 1 – Tritium concentration of Chicago rains, North American river water (mainly the Mississippi River), and New Mexico rains and surface waters; the T unit is defined as 10^{-18} atoms of tritium per atom of protium

TABLE 1 – *New Mexico water samples*

Sample no.	Collection date	Location	*T* units
144[a]	Feb. 7, 1954	El Rito de Los Frijoles, Jemez Mountains	27.2±0.4
145[a]	Feb. 7, 1954	Rio Grande, northwest of Santa Fe	6.6±0.2
146[a]	Feb. 22, 1954	Winsor Creek, near Cowles	9.9±0.2
200[b]	June 25, 1954	Los Alamos, rain	1160±100
203[b]	June 25, 1954	Los Alamos, rain	1000±100
207[b]	June 26, 1954	Los Alamos, rain	1550±120
201[b]	July 23, 1954	Mount Withington, thunderstorm	100±5
202[b]	July 27, 1954	Mount Withington, thunderstorm	106±10
224[c]	Sep. 11, 1954 to Oct. 1, 1954	Mount Withington, accumulated rains	19±1.4
52[d]	May 2, 1956	Rio Grande River, near Socorro	57.9±6
50[d]	Oct. 17, 1956	Socorro, rain	63.5±7
74[d]	Jan. 4, 1957	Socorro, rain	42.0±4
86[d]	Feb. 1, 1957	Rio Grande River, near Socorro	47.5±5
89[d]	Feb. 17, 1957	Socorro, rain	57.5±6
93[d]	Feb. 23, 1957	Pecos River, near Carlsbad	33.8±4
99[d]	Mar. 20, 1957	Socorro, rain	73.9±8

[a] *von Butllar* and *Libby* [1955].
[b] *Begemann* and *Martell* [1955].
[c] *Begemann* and *Libby* [1957].
[d] Collected and analyzed by the authors.

provided a relatively sharp and distinct marker for rain water falling in the northern hemisphere. Shortly after the explosion, the tritium content of this water attained a peak and subsequently returned almost to the prebomb level within a few months. A second series of bomb tests provided another tritium peak in 1956. Libby and coworkers [*Kaufman* and *Libby*, 1954; *von Buttlar* and *Libby*, 1955; *Begemann* and *Libby*, 1957] have monitored rainstorms at Chicago since 1952. Their data are plotted in Figure 1 to show the variation of tritium concentration with time. Similar results have been found for rainfall at Ottawa, Canada, by *Brown* and *Grummitt* [1956]. Available data indicate that New Mexico rains exhibit approximately the same variations (see Table 1 and the worldwide data reported by *Begemann* and *Libby* [1957]).

Radically different concentrations of tritium result from these atmospheric sources (see Fig. 1). The following criteria can thus be established for the proposed use of atmospheric tritium in the study of ground water:

(1) Water with unmeasurable tritium content may be said to be old; that is, to have been underground more than approximately 30 years and to be unmixed with recent meteoric water.

(2) Water under the ground before 1954 and unmixed with recent meteoric water can be dated within limits imposed by the radioactive decay rate, and with an accuracy determined by the range of variability of natural tritium contamination and the accuracy of the measuring technique

In a similar way *Kaufman* and *Libby* [1954] have dated wines of different vintages.

(3) Water containing a large amount of tritium relative to that expected from cosmic-ray sources in natural rain can be said to be recent; that is, to have a surface origin since 1954, or to have been strongly mixed with recent surface water.

(4) In some cases, where detailed information is available concerning the tritium concentration of underground water as a function of time, the peak in tritium concentration caused by a bomb explosion can be utilized to fix with reasonable precision the time of origin of the water as surface rain. Such data can be used also to infer the rate of flow of the water and the size of the reservoir into which the bomb tritium has been mixed.

Even though the measuring techniques for the tritium concentration of water have been perfected to such an extent that the error of a single measurement is of the order of ten per cent, it must be kept in mind that the interpretation of the data as to their hydrologic significance is likely to be difficult. It is the intent of this paper, therefore, to point out the type of problem which can be attacked rather than to present a completed areal hydrologic study.

The conduct of thermonuclear reactions which produce tritium in the free atmosphere may impose definite limitations in the future upon the techniques employed for tracing water by the use of atmospheric tritium. Under conditions of more frequent bomb testing, a peak found in ground water could not be attributed with certainty to a particular thermonuclear reaction.

Apparatus—Even though testing of a large bomb may increase the tritium concentration of the atmosphere many fold over that due to natural causes, the concentration expressed as a ratio of tritium to protium (hydrogen of mass 1) will be extremely small; of the order of 10^{-16}. *Kaufman* and *Libby* [1954] and *von Buttlar* and *Libby* [1955] have described apparatus and outlined procedures for enriching the tritium in water by electrolysis, and for measuring its concentration by the use of the low-level counting technique. The apparatus employed at the New Mexico Institute of Mining and Technology is similar to that used by Libby and coworkers. Although each sample requires two months of electrolysis time, many samples (in our case 25) can be processed concurrently.

Measurements of the amount of tritium are not affected by impurities in the water or by the type of storage vessels used, since the water samples are distilled several times preparatory to making the final measurements.

The relationship $T/T_0 = (V_0/V)\,(DV/D_0V_0)^{\alpha/\beta}$ holds between the tritium enrichment and the deuterium enrichment in the process of electrolysis. The symbols used are:

T	tritium concentration of the enriched sample as measured by its level of radioactivity
T_0	tritium concentration in the sample prior to electrolysis
V	volume after electrolysis
V_0	volume before electrolysis
D	deuterium concentration of the enriched sample
D_0	deuterium concentration before electrolysis
α	separation factor for deuterium
β	separation factor for tritium

The ratio β/α is believed to be constant; its value was determined by Kaufman and Libby to be 2.1 ± 0.1.

In the present study, values taken for V_0 varied from 2 to 6 liters; values for V between 0.2 and 0.3 ml. The quantity D was determined by the falling-drop method as described by *Kirschenbaum* [1951]. The initial deuterium concentration is known to vary somewhat in nature [*Friedman*, 1953], but for the present work an average value of 0.0142 mole per cent is assumed.

Geiger tubes of effective volume of about 0.425 liter are filled to 2 cm mercury pressure of ethylene, 3 cm of argon, and 5 to 20 cm of sample hydrogen, to determine the tritium activity of the enriched sample. Good plateaus of several hundred volts length in the neighborhood of 1300 v are obtained through the use of an electronic quench circuit with eight milliseconds dead time after each pulse. The counters are surrounded by a ring of 11 anticoincidence counters, and the entire arrangement is shielded by six inches of steel. The background of the sample counters when filled with unenriched hydrogen is 155 counts per minute without, and 18 counts per minute with, the anticoincidence ring in operation. Experiments are in progress to reduce the background further.

Comparison with the same tritium standard used in the Libby laboratory indicates that one count per minute per cm pressure of hydrogen gas in the counters used at this laboratory corresponds to 3.5×10^4 T units, the T unit being defined as a tritium concentration of 1×10^{-18} atoms of tritium per atom of protium.

It is estimated that the overall error in each

TABLE 2 – *Some New Mexico ground-water samples*

Sample no.	Collection date	Location	*T* units
66	Nov. 26, 1956	Secondary-recovery oil well, near Riverton, Wyoming	56.9
92	Apr. 25, 1956	Circle Mesa quadrangle[b]	3.1[a]
54	Apr. 25, 1956	Circle Mesa quadrangle[b]	9.9
55	Apr. 25, 1956	Circle Mesa quadrangle[b]	22.0
90	Feb. 23, 1957	Carlsbad Caverns, King's Palace	19.5
91	Feb. 23, 1957	Carlsbad Caverns, left wing	6.5

[a] Samples for which the error of the measurement probably exceeds 10 pct.

[b] Collector: Frederick C. Trauger, geologist, U. S. Geological Survey, Albuquerque, N. Mex.

tritium assay is about 10 pct; certainly not higher than 15 pct. This error can be tolerated in view of the large tritium-concentration difference in the samples investigated. If a sample count of 1 cpm/cm pressure of hydrogen can be distinguished from the background, the detection limit at a tritium enrichment of 10^4 is 3.5 *T* units. Actually, samples having a smaller activity can be counted, but the error of the measurement may then exceed 10 pct because of the inherent uncertainty connected with the background when gas counting is employed.

Illustrations of the application of the tritium method to ground-water samples—The simplest problem which can be solved by the application of the tritium method is that of determining the 'apparent age' of a water sample. As stated above, water containing less tritium than the detection limit of the apparatus has an age greater than about 30 years, whereas water containing more tritium than the prebomb natural level has an apparent age of less than three years, even though it may be a mixture of older water with water less than three years old which contains bomb tritium. Water, on the other hand, which has a tritium concentration of between 0 and, say, 10 *T* units has an apparent age of between 3 and 30 years, even though it may represent a mixture of older and younger waters.

Water definitely younger than three years was found in a sample from an oil well in Wyoming (Table 2, sample 66), where water flooding is employed for secondary recovery. This showed clearly that the water pumped from the well was derived from the injection water. The implications of this measurement will be discussed more fully in a separate paper.

Samples from the Carlsbad Caverns reveal fairly recent origin of the water. The King's Palace sample (Table 2, No. 90), which shows a relatively high tritium concentration, indicating the presence of bomb tritium, has an apparent age of less than three years; the sample from the left wing (Table 2, No. 91) shows an apparent age of between three and 30 years. Both samples definitely contain water of fairly recent origin.

Tritium determinations also can provide information concerning the process of recharge of underground aquifers. It is reasonable to expect some tritium to be present in the near-surface layers of ground water originating from rainfall with elevated tritium content, the tritium concentration being related to the degree of recharge.

Samples of three wells (Table 2, No. 54, 55, 92) from Circle Mesa quadrangle, Silver City, New Mexico, were selected to study this relationship. These wells are drilled into the Tertiary(?)-Quaternary alluvium. The samples were collected on April 25, 1956, a time when, owing to the 1956 bomb tests, the tritium content of the rain water was well above the background level.

The well from which sample 92 was taken is 250 ft deep and shows no depth-to-water fluctuation during the past two years, indicating very little local recharge. The tritium content is low.

The depth to water of the well from which sample 55 was taken has varied between 28 and 65 ft during the past two years, indicating appreciable local recharge. This sample shows a relatively high concentration of tritium.

The third well has fluctuated between 89 and 96 ft during the same period of time, corresponding to a moderate amount of local recharge. The tritium content found in sample 54, from this well, was intermediate to those of the other wells.

These findings are consistent with the assumption that the tritium technique yields information as to the extent of local recharge.

An interesting type of ground water is that discharged by hot springs. Libby and coworkers have analyzed the water from hot springs from a number of different areas. They conclude that such springs generally contain water of recent meteoric origin.

A spring of this kind provides the principal source of the municipal water supply of Socorro, New Mexico. The city obtains its water from two sources, a hot spring and a well. The spring is located about 1.5 mi west of the well; its ground elevation (4890 ft) is about 150 ft higher than the well. It is believed [*Waldron*, 1956] that the spring derives its water from the ground-water table in the Snake Ranch Flats (close to Socorro Mountain, 5800 ft), which is recharged from the Magdalena Mountains situated about ten miles west of Socorro. The water probably travels through a permeable zone, or through fractures under Socorro Mountain, and rises along a major fault which coincides with the eastern limits of Socorro Mountain. The well, on the other hand, taps the Rio Grande water table and does not receive a large contribution from the water feeding the spring.

TABLE 3 – *Socorro municipal water supply*

Sample no.	Collection date	Description	T units
3	Oct. 17, 1955	Socorro laboratory tapwater	9.5^{a}
6	Jan. 16, 1956	Socorro laboratory tapwater	6.3^{a}
14	Mar. 1956	Socorro laboratory tapwater	6.6^{a}
41	Sep. 25, 1956	Socorro laboratory tapwater	7.0
63, 64, 65	Nov. 19, 1956	Socorro laboratory tapwater	15.5
97	Mar. 18, 1957	Well feeding Socorro municipal supply	5.7
98	Mar. 18, 1957	Hot spring feeding Socorro municipal supply	3.3

^{a} Samples for which the error of the measurement probably exceeds 10 pct.

The spring water would require a considerable period of time to travel underground from the Magdalena Mountains to the spring site, whereas the Rio Grande valley receives recharge mainly along the valley walls and through the river itself. The well, situated near the valley walls, would therefore be expected to discharge water with elevated tritium concentration sooner than the hot spring.

Assuming that the tritium value in November 1956 represents bomb tritium in the well only, it follows from the data of Table 3 that the bomb peak had not yet appeared in the hot-spring

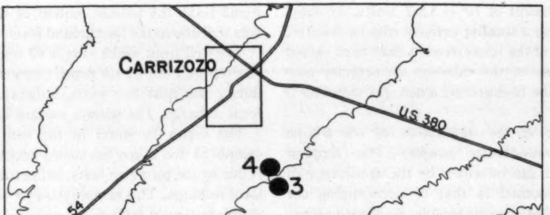

FIG. 2 – Map of the Carrizozo, N. Mex., sampling area indicating locations of the test wells

TABLE 4 – *Chemical analyses of the Carrizozo Wells*

Item	Well No.						
	1	2	3	4	6	7	8
Depth of well, ft	96	83	180	215	..	96	224
Depth from land surface to water (p = pumping), ft	76	p 72	98	48	20	..	p 69
Chemical analysis:							
Date, 1957[a]	May 28	May 28	Nov. 28[a]	Mar. 6	May 28	May 28	May 28
Temperature, °C	16.3	18.5	..	24	15.5	..	20
Silica, SiO_2	24	21	25	..	29	23	25
Calcium, Ca	109	127	212	238	254	125	210
Magnesium, Mg	69	55	56	51	78	44	44
Sodium + potassium	63	52	81	69	117	60	68
Bicarbonate, HCO_3	392	289	147	122	264	183	190
Sulfate, SO_4	283	299	609	608	735	341	510
Chloride, Cl	52	72	126	139	150	80	102
Fluoride, F	0.4	0.4	0.1	0.3	0.5	0.3	0.5
Nitrate, NO_3	2.1	5.0	4.4	..	16	4.5	25
Total dissolved solids	796	773	1190	1380	1510	768	1080
Hardness, $CaCO_3$	556	543	760	804	954	493	705
Noncarbonate	234	306	639	..	738	343	550
Specific conductance, micromhos at 25°C	1190	1180	1630	..	2030	1170	1540
pH	7.6	7.3	..	7.5	7.4	7.4	7.4

[a] Except Well No. 3, 1955.

water. This would indicate an average velocity of the water feeding the spring of less than ten miles in three years, or less than 50 ft/day. Further monitoring of the hot-spring water may reveal a peak in the tritium concentration from which, among other quantities, a value for the velocity of flow can be determined.

The fact that the well water shows considerably less tritium in early 1957 than the Rio Grande water indicates that the river water does not mix immediately with the entire ground water. Tritium determinations on waters from other wells in the valley should reveal information concerning the mixing rate.

The relatively few examples discussed above indicate the versatility of the tritium method when applied to ground-water problems. Even a single measurement may provide information which is difficult to obtain by other means. It should be kept in mind, however, that in general a ground-water table represents by no means a simple system. More detailed studies, therefore, are necessary before the hydrology of a larger area can be understood. An investigation of this kind is discussed in the next section.

Tritium study of wells near Carrizozo, New Mexico—Rain or river water entering the underground system at the recharge areas subsequently flows underground with a velocity proportional to the inclination of the water table and to the permeability of the formation. At the instant of recharge, the tritium concentration is identical with that of the surface water in the area. During subsequent underground flow, radioactive decay and mixing with older water diminish the tritium concentration. The detection of the bomb peaks in the tritium concentration of wells along the downslope of mountains should reveal information concerning the rate of water flow from the recharge area to the well site, provided no recharge takes place along the downslope. If the recharge area is known and can be approximated by a point or a line, the rate of flow can be inferred, for example, from the time of appearance of the 1954 or 1956 peak in tritium concentration at a well site of known distance from the area of recharge or at two wells of known distance apart. Also, the peak height enables one to infer the size of the ground-water reservoir into which the tritiated water has mixed.

In order to determine the applicability of the tritium method to the problem of ground-water flow, an area south of Carrizozo, New Mexico, was selected for study (see Fig. 2). Chemical analyses of these waters are shown in Table 4. This area was chosen for the following reasons:

(1) Recharge is believed to occur mainly in the mountain range lying to the south.

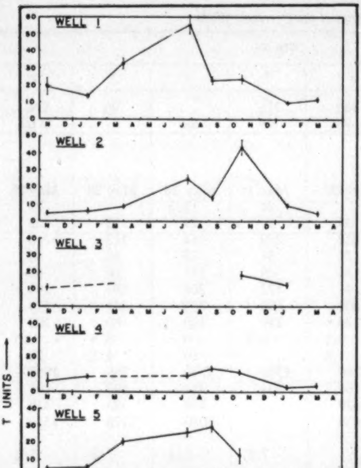

FIG. 3 – Tritium concentration peaks found in the test wells of the Carrizozo area

(2) The water table is inclined to the northwest and drops about 0.1 mile per mile, so that a reasonably high flow rate may be expected.

(3) Until very recently, no large quantity of water was pumped from the aquifer for irrigation purposes. The tested wells are all stock wells, with the exception of the municipal well of Carrizozo, which is pumped at the rate of 200 – 600 gallons per minute. Thus, recycling of irrigation water does not occur.

(4) The municipal water supply of Carrizozo presents a serious problem as to its quantity and quality. Investigations using the tritium method may be helpful to this community.

The area has been subjected to various types of geophysical exploration by the New Mexico Institute of Mining and Technology. A preliminary report by *Weber* and *Holmes* [1951] describes briefly the geological environment and lists resistivity measurements of the ground. It is apparent from their work that the valley contains two groups of water-bearing formations. The upper horizon consists of Quaternary alluvium having a saturated thickness of about 100 ft below the water table, which in turn lies at a depth approximately 100 ft below the land surface. The bedrock consists of Cretaceous sandstone and shale, the sandstone beds carrying low-quality ground water. These beds crop out near the 5300-ft contour line east of the village of Carrizozo, as evidenced by a number of perennial springs.

Samples for the tritium analysis were taken from the eight wells shown in Figure 2 at intervals of two to three months. Wells 1, 2, 5, 6, and 7 are shallow and tap only the alluvial water table. Wells 3, 4, and 8 are deeper and probably penetrate into the Cretaceous beds. Only well 4 (the municipal well) is heavily pumped. Wells 1, 2, 5, 7, and 8 are stock wells; wells 3 and 6 were not used during the time of the investigation.

As seen from Figure 3, marked peaks occurred during the summer and fall of 1956 in most of the wells investigated. Two interpretations are suggested:

(1) It may be assumed that the peaks represent the 1954 bomb tritium which went underground on the forested mountaintops to the south and southeast. If this is the case, well 1 should reach its tritium maximum first. The three wells 2, 5, and 6 should follow next; then well 7, well 8, and finally wells 3 and 4. It is obvious that well 1 had its peak before any other well, most of the others following approximately in the order indicated. Well 4 did not exhibit a marked peak. Insufficient data were obtained to determine whether or not a peak occurred in well 3. Further observation will show whether wells 3 and 4 will show their peaks at a later time. The interpretation of the wide peak found for well 8 is difficult. Possibly this water represents the mixing of water from two or more sources having different tritium concentrations caused by dissimilar trajectories. This is possible, since the well is deep and taps several water layers.

The average peak height exhibited by the wells was about 50 *T* units, with surprisingly little variation. The average peak tritium concentration of rainfall during the summer of 1954 was about 500 *T* units. This would mean that the 1954 recharge had to be diluted ten-fold in the ground-water reservoir. The ground-water inventory, therefore, must be at least ten times the amount of recharge in that year.

The width of the well peaks, except for well 8, is of the same order of magnitude as the tritium peak found in the 1954 rainfall (see Fig. 1). This would indicate that the underground flow is fairly uniform.

On the assumption that the peaks are due to the 1954 bomb test, the time lag occurring between the maxima of the peaks for the different wells is compatible only with a flow rate in excess of 50 ft/day. Insufficient data concerning the rate of flow of water through the water-bearing strata of this area are available to determine whether or not this is a reasonable value.

(2) Another possible assumption is that the well peaks represent the 1956 tritium peak of rain that found its way into the ground water soon after it fell. This would mean that direct recharge of the aquifer occurs along the downslope. All the wells might be expected to have their peaks at the same time shortly after the rainfall containing a high tritium concentration had occurred. In this case the occurrence of peaks would not be related to the lateral velocity of the ground-water motion. Further detailed studies will be required, however, to reveal the rate of percolation of surface water into the aquifer.

If an average value of 300 *T* units is assumed for the 1956 summer rains, the well-peak maxima of about 50 *T* units would indicate that the water pumped from the wells in the fall of 1956 contained recent rain water to the extent of 10 to 20 pct. Water-table-fluctuation determinations, if available, would indicate whether or not this is possible. It is strange that all the wells that exhibit peaks should mix to approximately the same degree even though they are of different depths.

The peak width of the tritium-concentration curves for the wells is of the same order of magnitude as the peak width of the 1956 rainfall curve. The delay of the peak maxima of the wells with respect to the rainfall may be related to the time required for percolation through the overburden of the aquifer. As most of the rainfall occurred in July and August (see Fig. 4), the data indicate a rate of percolation of approximately one foot per day.

The fact that the well peaks are sharp and drop rather quickly in early 1957 to values comparable to prebomb rain water is difficult to understand if the peaks are due to the 1956 bomb test. The vertical percolation with subsequent lateral motion should have caused peaks of greater duration. Only if the vertical diffusion of tritium through the aquifer is very rapid (about 10 cm/day) and is the rate-determining factor, can the shape of the peaks be explained. The rainfall at the nearby city of Ruidoso, which is situated at about the same altitude as the Carrizozo sampling sites, and where the amount of rainfall is similar, is plotted in Figure 4. The scanty precipitation between August 1956 and February 1957 may account for the return of the tritium concentration to such low values.

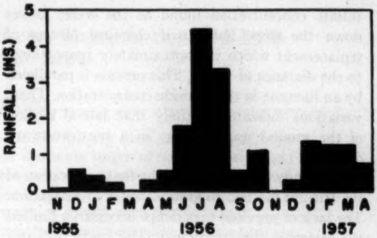

FIG. 4 – Official rainfall data for Ruidoso, N. Mex., taken from the New Mexico *Climatological Data* [U. S. Weather Bureau]

Arguments against this interpretation are that the total mixing would have to be the same for every well, as indicated by the similar peak heights, and that well 8, even though it is very deep, reaches the same maximum value.

From these considerations it appears likely that the tritium peaks exhibited by the ground water are those of the 1954 rainfall, although additional data are needed before final conclusions can be drawn.

Chemical analyses (Table 4) were obtained of the waters from all wells except 5, which recently has been dismantled. The chemical analyses show that the total amount of solids dissolved in the water generally increases toward the valley. The only exception is well 6; this may be due to stagnation of the water in the unused well or to a local high concentration of soluble materials in the soil. A high nitrate concentration in wells 6 and 8 possibly indicates greater surface-water contamination. The calcium and bicarbonate concentrations found in all the wells indicate that the water has previously moved through a limestone layer. The gradually decreasing bicarbonate and increasing sulfate concentration found as the water moves down the slope indicate a chemical process of replacement which is approximately proportional to the distance of travel. This process is paralleled by an increase in the chloride concentration. These variations indicate definitely that lateral motion of the ground water occurs in a northwestward direction.

The study at Carrizozo is the first application of the tritium method to ground-water investigation. The lack of previous experience necessarily limited the design of the experiment. The study indicates that the following factors should be kept in mind for future work:

(1) The simplest problem of analysis with reference to the rate of flow obtains where the wells in question tap only one ground-water layer. Otherwise the pumped water may be a mixture of waters of varying age from different levels, since perforated well casings sample a considerable vertical range of the aquifer. In this case, nevertheless, inference can be drawn as to the presence and character of the different water layers.

(2) For the investigation of ground-water flow, there should be reasonable evidence that no recharge of the aquifer occurs between the wells under investigation. On the other hand, if recharge occurs, the rate and extent of percolation can be determined.

(3) Areas which are heavily pumped for irrigation purposes, and where recycling of the irrigation water may obscure the tritium concentration peaks, should not be used for the determination of flow velocity. The extent of recycling can be inferred, however, from tritium measurements.

(4) In order to establish more accurately the time, height, and width, of the tritium peaks, a more frequent sampling schedule than that used in the present study is recommended. It is not necessary, however, that all samples be analyzed, since frequent samples are of value only at or near the peaks.

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Factors Affecting Sediment Delivery Rates in the Red Hills Physiographic Area

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Abstract—Twenty-five records of watershed sediment delivery rates and factors affecting sediment-delivery rates are analyzed. Relief and maximum length of watershed expressed as relief-length ratio (R/L) in a simple curvilinear correlation or as individual variables in a multiple curvilinear correlation are found to offer a much closer correlation with sediment-delivery rates than size of sediment contributing area or several other factors tested.

The basic trend of thought in this study is that rates of sediment yield of watersheds are immediately comparable only if their gross erosion rates per unit of area are the same. Otherwise, it is their delivery rates that must be compared, and once causal factors of the sediment-delivery rate have been evaluated for a soil and climatic region, it is possible to predict sediment yields closely from gross erosion data and the delivery rate characteristics of individual watersheds within that region.

Introduction—This paper presents the results of sediment-delivery rate studies of a group of reservoirs and their watersheds in the Red Hills physiographic area, a sub-division of the central lowlands province in extreme southern Kansas, western Oklahoma and western Texas (Fig. 1). The area corresponds generally to the Rolling Red Plains land resource area.

Sediment delivery rates have been investigated in the Blackland Prairies of Texas and the Loess Hills in eastern Nebraska, western Iowa, southwestern Minnesota and southeastern South Dakota. *Maner* and *Barnes* [1953], in a study of the Texas Blackland Prairies, found that the size of net sediment contributing area is an excellent indicator of the delivery rate of watersheds within a given size range. In fact, difference in size of net sediment contributing area accounted for approximately 93 pct of the variation in sediment-delivery rates between a group of watersheds ranging in size from 0.43 to 8.71 sq mi. The results of that study indicate uniformity among other watershed characteristics which have an influence on sediment delivery rates in that physiographic area. To demonstrate the fact that variables other than size of net sediment contributing area may have an important bearing upon sediment delivery rates, *Glymph* [1954] developed a delivery rate equation from Loess Hills sedimentation data previously presented by *Gottschalk* and *Brune* [1950]. In this case difference in size of net sediment contributing area explained only 18 pct of the variation in sediment delivery rates of a group of watersheds ranging in size from 0.038 to 41.3 sq mi. The results of his study indicate that unless factors which influence sediment delivery rates are uniform for all watersheds, within a given area, the ratio of sediment yield to gross erosion may be expected to show considerable variation for equal size sediment contributing areas even within the same physiographic area.

Sediment delivery rate, defined by *Glymph* [1954], as the ratio between annual sediment yield and annual gross erosion, is dependent upon a number of watershed factors and the study presented here has been undertaken to develop a procedure in which measurable watershed characteristics are used to make acceptable estimates of sediment delivery rates. The factors tested include length, relief, shape, size of net sediment contributing area, weighted average land slopes, channel density, and relief-length ratio.

The study included the following six steps: (1) tabulation of existing reservoir sedimentation survey data after making adjustments for reservoir trap efficiency and size of net sediment contributing area to determine total sediment yield and rate of sediment yield per square mile of net sediment contributing area, (2) estimation of gross erosion rates during period of sediment record, (3) sediment delivery rates were computed from data obtained in steps (1) and (2), (4) detailed studies were made of the watershed of each reservoir to assemble quantitative data on physical characteristics which were thought to influence downstream delivery of eroded material, (5) data obtained in step (4) were correlated with sediment delivery rates to develop a regression equation for estimating sediment delivery rates and (6) after developing the best equation for estimating

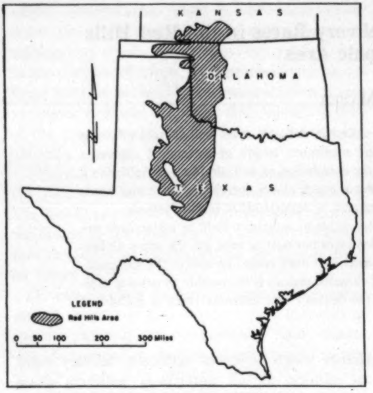
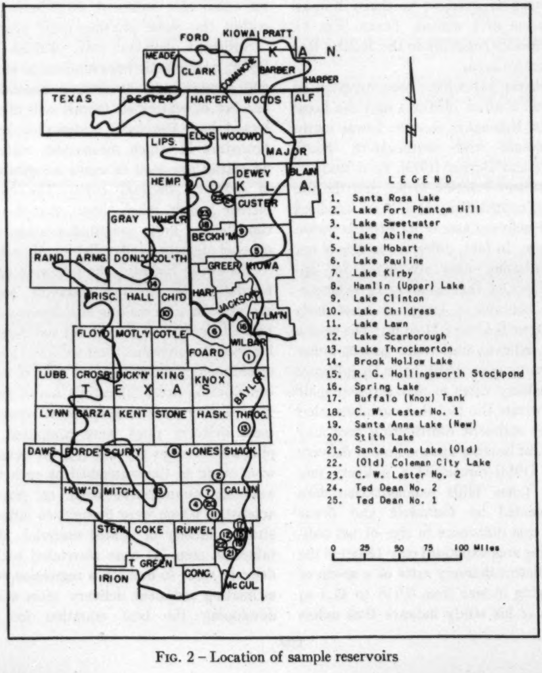

KANSAS
OKLAHOMA
TEXAS
LEGEND
Red Hills Area
0 50 100 200 300 Miles

FIG. 1 – Location of Red Hills area

sediment delivery rates, a study was made to determine the characteristics of the independent variables used in the equation.

Sediment yield data—Twenty-five reservoirs on which sedimentation survey data are available were selected for use in developing the watershed sediment-yield values used in this study. Other reservoirs in this physiographic area were eliminated from the study for one or more of the following reasons: net sediment contributing area of more than 350 sq mi, breached dam during period of sediment record, doubtful trap efficiency of reservoir, and inaccuracy of reservoir sedimentation survey data, judged principally on the method of survey used. For example, reconnaissance surveys with only a few random observations throughout a reservoir were not considered to be within the range of accuracy adopted in this study. The sample reservoir locations are shown in Figure 2.


FORD
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ALF
LIPS.
ELLIS
WOODWD
MAJOR
HEMP.
DEWEY
O K L A.
BLAIN
CUSTER
GRAY
WHEL'R
BECKH'M
RAND.
ARMG.
DONLY
COL'TH
GREER
KIOWA
BRISC.
HALL
CHI'D
HAR'
JACKSON
TILLM'N
FLOYD
MOTL'Y
COT'LE
FOARD
WILBAR
LUBB.
CROSB'
DICK'N'
KING
KNOX
BAYLOR
T E X A S
LYNN
GARZA
KENT
STONE
HASK.
THROC.
DAWS.
BORDE'
SCURRY
JONES
SHACK.
HOW'D
MITCH
CALL'N
STERL
COKE
RUN'EL
T. GREEN
IRION
CONC.
McCUL.
LEGEND
1. Santa Rosa Lake
2. Lake Fort Phantom Hill
3. Lake Sweetwater
4. Lake Abilene
5. Lake Hobart
6. Lake Pauline
7. Lake Kirby
8. Hamlin (Upper) Lake
9. Lake Clinton
10. Lake Childress
11. Lake Lawn
12. Lake Scarborough
13. Lake Throckmorton
14. Brook Hollow Lake
15. R. G. Hollingsworth Stockpond
16. Spring Lake
17. Buffalo (Knox) Tank
18. C. W. Lester No. 1
19. Santa Anna Lake (New)
20. Stith Lake
21. Santa Anna Lake (Old)
22. (Old) Coleman City Lake
23. C. W. Lester No. 2
24. Ted Dean No. 2
25. Ted Dean No. 1
0 25 50 75 100 Miles

FIG. 2 – Location of sample reservoirs

TABLE 1 – *Location, size of net sediment contributing area, period, and length of sediment record of each reservoir*

Record (1)	Name of reservoir (2)	Location (3)	Net sediment contributing area[a] (4) sq mi	Period of sediment record (5)	Length of sediment record (6) yr
1	Santa Rosa Lake	Vernon, Texas	332	1929–1948	18.2
2	Lake Fort Phantom Hill	Abilene, Texas	252	1938–1953	14.8
3	Lake Sweetwater	Sweetwater, Texas	104.1	1930–1941	11.8
4	Lake Abilene	Abilene, Texas	93.6	1921–1948	27
5	Lake Hobart	Rocky, Okla.	51.88	1933–1937	4
6	Lake Pauline	Quanah, Texas	40.0	1905–1938	33
7	Lake Kirby	Abilene, Texas	34.05	1928–1951	13.2
8	Hamlin (Upper) Lake	Hamlin, Texas	31.8	1917–1941	24.6
9	Lake Clinton	Canute, Okla.	22.16	1930–1950	19.8
10	Lake Childress	Childress, Texas	13.7	1922–1938	16
11	Lake Lawn	Lawn, Texas	11.55	1911–1941	30
12	Lake Scarborough	Coleman, Texas	9.85	1923–1940	17
13	Lake Throckmorton	Throckmorton, Texas	6.26	1918–1954	35.7
14	Brookhollow Lake	Memphis, Texas	3.2	1929–1938	9
15	R. G. Hollingsworth[b]	Burkett, Texas	2.44	1937–1941	3.7
16	Spring Lake	Vernon, Texas	2.41	1911–1938	27
17	Buffalo (Knox) Tank	Burkett, Texas	1.71	1900–1941	41
18	C. W. Lester No. 1[b]	Cheyenne, Okla.	1.59	1945–1949	4
19	Santa Anna Lake (new)	Santa Anna, Texas	1.00	1923–1940	17
20	Stith Lake	Lawn, Texas	0.95	1926–1941	14.6
21	Santa Anna Lake (old)	Santa Anna, Texas	0.78	1910–1940	30.5
22	Coleman City Lake (old)	Coleman, Texas	0.69	1906–1940	33.6
23	C. W. Lester No. 2[b]	Cheyenne, Okla.	0.63	1944–1949	5
24	Ted Dean No. 2[b]	Cheyenne, Okla.	0.164	1941–1955	14
25	Ted Dean No. 1[b]	Cheyenne, Okla.	0.036	1944–1955	11

[a] Excluding area of reservoir and the combined drainage areas of average number of stockponds in watershed during period of sediment record.

[b] Stockpond.

Sediment-yield values for the sample watersheds were established by adjusting measured reservoir sediment production rates for reservoir trap efficiency and net sediment contributing area. In estimating the trap efficiency of each reservoir, the method based on capacity-inflow ratio (C/I) developed by *Brune* [1953] was used. The net sediment contributing area of each watershed was determined by substracting reservoir area and average total area behind upstream stockponds from the total drainage area. Sediment contributing areas range from 0.036 to 332 sq mi; however, 64 pct of the reservoirs have sediment contributing areas of less than 15 sq mi.

Sedimentation surveys of the sample reservoirs were made by the Soil Conservation Service during the period from November 1937 to March 1955. The ages of the reservoirs (length of sediment record) at the time of survey ranged from 3.7 to 41.0 years with an average age of 19.0 years. Only three of the reservoirs (records 5, 15, and 18) were under five years of age at the time of survey; therefore, sediment yield values are thought to be representative of the long-time mean. Table 1 gives the location, size of net sediment contributing area, period of sediment record and length of sediment record of each reservoir studied. Column 5 of Table 2 gives the sediment yield values of each reservoir watershed.

Gross erosion rates—Studies were made of the watershed above each reservoir to develop data for estimating the annual rate of gross erosion per square mile of net sediment contributing area. This rate was estimated by computing separately the amount derived from sheet erosion and the amount derived from channel erosion.

The average quantity of material derived from channel erosion, including gullies, was estimated from watershed channel density data and data on annual rates of channel enlargement obtained by comparing channel development on early and recent watershed aerial photographs (period between photographs varied from 8 to 16 years).

Annual sheet erosion rates were computed by the *Musgrave* [1947] method in a manner previously described by *Barnes* and *Maner* [1953]. According

TABLE 2 – *Gross erosion, sediment yield, and delivery rate*

Record (1)	Estimated average dry weight of soil (2)	Estimated annual rate of gross erosion per square mile (3)		Estimated average dry weight of sediment (4)	Annual rate of sediment yield per square mile (5)		Delivery rate (per cent of gross annual erosion) (6)
	lb/cu ft	ac ft	ton	lb/cu ft	ac ft	ton	pct
1	82	7.05	12,591	52	0.73	827	7
2	78	3.87	6,575	43	0.72	675	10
3	79	1.46	2,511	44	0.43	412	16
4	77	1.06	1,778	38	0.23	190	11
5	74	7.90	12,735	36	1.56	1,223	10
6	82	6.83	12,198	52	1.53	1,733	14
7	78	3.14	5,335	43	1.16	1,087	20
8	84	1.17	2,141	60	0.15	196	9
9	85	7.60	14,069	65	2.81	3,978	28
10	84	3.41	6,240	60	1.47	1,921	30
11	78	3.29	5,590	43	0.53	497	9
12	78	2.67	4,536	43	0.89	834	18
13	78	2.74	4,655	43	0.54	506	11
14	84	2.75	5,033	60	1.28	1,673	33
15	78	2.96	5,029	43	0.84	787	16
16	84	2.20	4,026	60	0.35	457	12
17	78	0.62	1,053	60	0.07	91	9
18	80	8.00	13,936	48	3.25	3,396	24
19	78	2.54	4,315	43	1.26	1,181	27
20	81	2.14	3,775	52	0.69	782	21
21	78	2.94	4,995	43	1.49	1,396	28
22	77	2.35	4,300	60	0.68	889	21
23	80	1.80	3,135	48	1.07	1,118	35
24	86	1.60	2,997	68	1.08	1,599	53
25	86	0.96	1,798	68	0.72	1,066	59

to Musgrave's findings, based on data from 19 widely scattered research stations, annual soil loss rate from sheet erosion is a function of the inherent erodibility of the soil, degree of land slope in per cent, length of land slope in feet, cover factor and maximum 30-minute rainfall, two-year frequency, in inches. As a result of his findings, soil loss from sheet erosion can be expressed by the equation

$$E = FRS^{1.35} L^{0.35} P_{30}^{1.75} \qquad (1)$$

where

E = sheet erosion, inches per year
F = soil factor, basic erosion rate, inches per year
R = cover factor
S = land slope, in per cent
L = length of land slope, in feet
P_{30} = maximum 30-minute rainfall, two-year frequency, in inches

Estimated annual rates of gross erosion per square mile of net sediment contributing area are shown in Table 2, Column 3.

Delivery rate—The rates of sediment yield of watersheds are immediately comparable only if their gross erosion rates per unit of area are the same. Otherwise, it is their delivery rates that must be compared. This may be observed, for example, from the records of two watersheds (record 7 and record 25) with almost identical rates of sediment yield of 1087 tons and 1066 tons, respectively, per unit of area. If the watershed with a rate of sediment yield of 1087 tons has an erosion rate of 5335 tons, its yield-erosion ratio is 0.20, while if the watershed with a rate of sediment yield of 1066 tons has an erosion rate of 1728 tons its yield-erosion ratio is 0.59. Although rate of sediment yield is practically the same for both watersheds the great difference in yield-erosion ratios should correspond to proportional differences in watershed characteristics. Based on this reasoning, the ratio between annual rate of sediment yield and annual gross erosion rate per square mile of sediment contributing area was computed for each watershed. This ratio, called the delivery rate, is expressed in per cent, and treated as the dependent variable in the correlation analysis of data. Table 2, Column 6 shows the sediment delivery rate of each watershed.

Watershed physical surveys—Detailed studies were made of the watershed of each reservoir to assemble quantitative data on physical characteristics which were considered to influence downstream delivery of eroded material. The variables studied are: (*S*) size of net sediment-contributing area in square miles; (*CD*) channel density, miles of channel per square mile of net sediment-contributing area; (*L*/*W* ratio), the ratio between maximum length and average width of watershed was considered as a shape factor; (*WS*) weighted average land slopes in feet per hundred feet; (*R*) watershed relief in feet defined as the difference in elevation between the average elevation of the watershed divide at headwaters of mainstem drainage and elevation of streambed at dam-site; (*L*) maximum watershed length in feet, measured approximately parallel to mainstem drainaged from dam-site to watershed divide and (*R*/*L* ratio) relief-length ratio (essentially the same as relief ratio as defined by Schumm [1954]) computed by dividing (*R*) by (*L*) for each watershed. Table 3 shows numerical values for each variable and the source of information.

Analysis of data—Correlation analyses were made in order to determine the relationship between sediment delivery rate and selected measurable watershed characteristics. In the analyses,

TABLE 3 – *Watershed physical surveys data*

Record (1)	Ratio, length to aver. width (2)	Channel density[a] (3)	Weighted average land slopes[b] (4)	Watershed relief[c] (5)	Maximum watershed length[e] (6)	Relief-length ratio (7)
		mi/sq mi	pct	ft	ft	
1	4.3	1.60	5.45	400	179,520	0.00223
2	4.4	1.97	3.37	840	163,680	0.00513
3	1.6	2.45	5.72	500	73,920	0.00676
4	3.0	3.50	6.39	545	105,600	0.00516
5	5.0	0.84	4.50	400	84,480	0.00473
6	1.8	4.00	3.00	150	24,445	0.00614
7	3.2	2.03	3.50	555	60,720	0.00912
8	1.4	2.50	3.26	213	62,832	0.00339
9	1.0	1.21	4.18	317	23,760	0.01334
10	2.0	1.35	4.50	150	8,448	0.01776
11	4.4	1.47	2.27	175	39,600	0.00441
12	3.1	2.20	6.47	300	33,000	0.00919
13	2.2	0.30	1.56	195	31,680	0.00616
14	1.0	4.70	8.00	200	11,880	0.01683
15	1.3	0.54	1.53	75	8,799	0.00852
16	2.0	0.20	2.54	100	15,840	0.00631
17	2.0	0.15	1.93	45[d]	10,948	0.00411
18	2.0	7.00	8.81	110[d]	10,400	0.01057
19	1.7	1.00	1.93	100	6,600	0.01515
20	2.0	0.37	1.93	58[d]	5,600	0.01036
21	2.2	0.50	1.67	100	5,800	0.01722
22	1.2	0.56	5.00	50[d]	4,714	0.01060
23	1.0	9.00	10.00	80[d]	3,934	0.02036
24	2.4	6.00	10.00	80[d]	2,482	0.03223
25	1.4	5.00	10.00	40[d]	1,056	0.03788

[a] Total channel length measured on aerial photographs and divided by net sediment contributing area.

[b] Computed from data in soil decline and conservation time table study files.

[c] Estimated from U.S.G.S. topographic sheets (except as shown under d).

[d] Computed using U. S. Army Type F-3 photo interpretation kit (parallax converted to height).

[e] Measured essentially parallel to mainstem drainage from dam-site to watershed divide.

delivery rate, expressed as the per cent of the annual gross erosion delivered to the reservoir, was treated as the dependent variable. Variables listed under watershed physical surveys were all considered as independent and were tested individually, in association with each other and in some cases two variables were combined and expressed in ratio form. The statistical method of analysis has been outlined by *Croxton* and *Cowden* [1953] and *Snedecor* [1940].

A scatter-diagram plotting of sediment delivery rate against each independent variable showed a definite departure from linearity in most cases. Similar plottings on logarithmic ruled paper indicated that the exponential growth curve would adequately describe the characteristics of the data. Thus, the numerical values of all variables were transformed either to logarithms or cologarithms for use in the regression analyses.

A study of the various plottings on log paper revealed that maximum length of watershed and relief of watershed when expressed as relief-length ratio plotted best with sediment delivery rates. Therefore, a non-linear correlation between relief-length ratio and sediment delivery rate was computed as the initial step in statistical analysis of the data. The regression equation for this correlation is

$$\log DR_e = 2.94259 - 0.82363 \text{ colog } R/L \text{ ratio} \quad (2)$$

where

DR_e = estimated sediment delivery rate in per cent of annual gross erosion

R/L = relief-length ratio

The standard error of estimate of (2) is ±0.04041 log units, and the coefficient of curvilinear correlation 0.987, which expresses a 97 pct account of the variation in sediment delivery rates. The empirical relationship of sediment delivery rate to relief-length ratio is presented in the form of the delivery rate curve Figure 3.

To determine the relative influence of relief and length of watershed, as individual independent variables, in estimating sediment delivery rates a multiple curvilinear correlation between these three variables was computed. The regression equation for this correlation is

$$\text{Log } DR_e = 2.96162 + 0.86868 \text{ Log } R - 0.85354 \text{ Log } L \quad (3)$$

where

DR_e = estimated sediment delivery rate in per cent of annual gross erosion

R = relief of watershed, in feet

L = maximum length of watershed, in feet

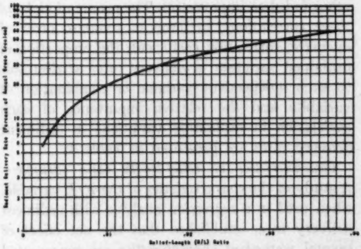

FIG. 3 – Sediment delivery rate curve

TABLE 4—*Results of cnrviliuear correlation analyses; dependent variable, sediment delivery rate*

Independent variables	Standard error of estimate	Coefficient of curvilinear correlation	Proportion of explained variation	Explained variation index
	log unit		pct	
Relief-length ratio (R/L)	±0.0404	0.987	97.3	1.00
Relief and length	±0.0537	0.979	95.8	0.98
Length	±0.1500	0.795	63.2	0.65
Length-aver. width ratio (L/W) and net contributing area	±0.1756	0.746	55.6	0.57
Net sediment contributing area	±0.1733	0.714	50.9	0.52
Length-aver. width ratio (L/W) (shape)	±0.2082	0.540	29.1	0.30
Relief	±0.2190	0.465	21.6	0.22
Weighted aver. land slopes	±0.2195	0.460	21.1	0.21

The standard error of estimate of (3) is ± 0.0536 log units, and the multiple correlation coefficient 0.979, which explains approximately 96 pct of the variation in sediment delivery rates. In this particular correlation when length of watershed is ignored or held constant the total correlation between relief and sediment delivery rate is −0.46509. On the other hand when relief is ignored or held constant the total correlation between length of watershed and sediment delivery rate is −0.79508. Further statistical manipulation of the results of this correlation revealed that length of watershed is approximately 1.5 times as effective in estimating sediment delivery rates as is watershed relief.

Subsequent testing of other independent variables individually and in association with each other failed to improve (2). The results of eight of these correlations, in terms of standard error of estimate, correlation coefficient, the proportion of explained variation in delivery rates attributable to each independent variable or combination of variables and the relative importance of each correlation in explaining variations in sediment delivery rates are presented in Table 4.

Characteristics of relief-length ratio variable—A study of the characteristics of the *R/L* variable, when used in a regression analysis with sediment delivery rate, established that the net effect of several watershed characteristics are represented in the derived equation for estimating delivery rate. For example, plottings on logarithmic paper revealed that *R/L* is related to the following measurable watershed factors: (1) Size (net sediment-contributing area). Large watersheds usually have lower *R/L* than smaller watersheds in the same area. (2) Shape (length-width ratio). Short, wide watersheds usually have higher *R/L* ratios than long narrow watersheds. (3) Alluvial soils area-net watershed area ratio. In contrast to high *R/L* ratio watersheds, low *R/L* ratio watersheds have a greater proportion of their total area in alluvial soils, indicating the positive influence of low *R/L* ratio watershed characteristics on upstream deposition. (4) Average land slopes. Generally high *R/L* ratio watersheds are associated with steep land gradients. (5) Average stream gradients are directly related to *R/L* ratio values. (6) Channel density. Generally greater channel density per unit of area is associated with higher *R/L* values.

Conclusions—(1) Sediment delivery rate in the Red Hills physiographic area is a function of several watershed characteristics which are related to and apparently adequately expressed by the variable relief-length ratio. However, the validity of the use of this variable in other areas must be established by adequate testing.

(2) Maximum length of watershed is approximately 1.5 times as effective in forecasting sediment delivery rates as is watershed relief.

(3) The influence of the maximum length of watershed on sediment delivery rate is conditioned by the total relief associated with maximum length. Likewise, the influence of a given watershed relief value on sediment delivery rate is conditioned by the distance eroded materials must travel between the high and low points used in computing watershed relief.

(4) The relatively close estimation of the per cent of gross erosional material delivered to a reservoir site from relief-length ratio data demonstrates that the rate of sediment yield to a structure site is subject to acceptable estimation, in the Red Hills physiographic area, if certain physical characteristics of the watershed are incorporated in the estimate and the gross erosion rate is known or can be computed.

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Effect of Temperature Distribution on Moisture Flow in Porous Materials

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Abstract—Several experimenters have observed moisture flow rates through porous materials under a temperature gradient, which are many times the calculated rates based on vapor diffusion. To investigate this discrepancy, a temperature gradient was applied across an enlarged model of a particular, high-quartz wet sand, and the temperature distribution within the pore spaces was measured. For the 'air-dry condition' of the model, the average temperature gradient in the pore spaces was six times the over-all applied gradient. Approximately this same ratio exists, therefore, between the respective vapor pressure gradients.

It is proposed that the flow mechanism consists of multiple vapor diffusion and liquid flow steps in series, the resistance to flow in the liquid phase being negligible, so that the flow rate is determined by the vapor pressure gradients in the pore spaces. The fact that these gradients are of the order of six times the over-all gradient previously used to calculate the flow rate at least partially explains the discrepancy.

Introduction—The mechanism by which water moves through a porous material when subjected to a temperature gradient has not yet been definitely established [*Bouyoucos*, 1915; *Smith*, 1943; *Winterkorn*, 1947; *Gurr* and others, 1952; *Taylor* and *Cavazza*, 1954]. The experimentally observed rate of flow from the hot to the cold side is found to be about ten times the calculated rate based on vapor diffusion [*Bouyoucos*, 1915; *Winterkorn*, 1947; *Taylor* and *Cavazza*, 1954]. It has been suggested that this lack of agreement between the experimental and calculated rate occurs because some of the water flows in the liquid (film) phase [*Winterkorn*, 1947].

Experiments designed to detect this flow in the liquid phase have been carried out in this laboratory. Flow in the liquid phase was not detected [*Kuzmak* and *Sereda*, 1957]. It therefore appears that the flow takes place in the vapor phase. If the flow does take place in the vapor phase, a possible reason for the discrepancy between the observed and calculated rates may be a discrepancy between the true vapor pressure gradient within the pores of the material and the vapor pressure gradient used in making the calculations.

This paper describes an experiment in which the temperature distribution in a model of a porous material was measured. From these measurements, temperature gradients were calculated. The corresponding vapor pressure gradients can also be calculated.

Experimental—The following considerations lead to the design of the model. The moisture in wet sand is presumed to be distributed as thin films on the surfaces of the solid particles, but mainly concentrated in wedge-shaped rings around the points of contact between adjacent particles. Referring to Figure 1, vapor flow may be assumed to occur under a temperature gradient by a process of evaporation in region A, diffusion across the air space, and condensation in region B. In an open system this does not result in a moisture gradient if equal suctions are maintained at the open boundaries. Assuming that the resistance to liquid flow from one side of the water ring A′A to the other is negligible, then the quantity that determines the rate of moisture flow under a temperature gradient is the average vapor pressure gradient in the pore space AB.

One method by which the vapor-pressure gradients in the pore space may be investigated is to determine the temperature distribution in the pore space and on its bounding surfaces since the temperature conditions are the cause of the vapor pressure conditions. A rigorous mathematical approach to the determination of the temperature distribution in such a system appears to be intractable unless simplifying approximations are made. The alternative is to construct an enlarged model of the grain-pore system, impose a temperature gradient upon the model, and measure temperatures at selected locations within the system after establishing thermal equilibrium.

The two extreme packing arrangements of a granular material composed of uniform spherical particles are the open and close packing arrangements. The open packing arrangement, wherein the spheres form a cubic lattice as in Figure 2, was selected for reasons of simplicity. By symmetry the planes through the horizontal full lines perpendicular to the plane of the figure, are all isothermal planes. Similarly the orthogonal planes through the vertical dashed lines are heat flow planes. Thus the temperature distribution in the

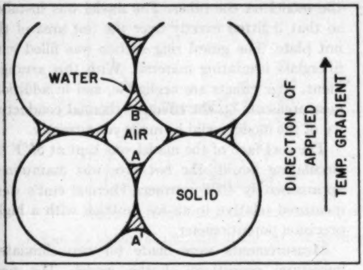

FIG. 1 – Representation of moisture distribution within the pore spaces of a granular material

space enclosed by the heavy full lines is representative of the distribution throughout the material. The model which was constructed is shown in Figure 3, and consisted of four marble hemispheres six inches in diameter, contained in a box, the top and bottom of which was $\frac{3}{8}$ inch aluminum and edges $\frac{1}{8}$ inch lucite.

The temperature distribution in such a system under a temperature gradient will depend upon the relative thermal conductivities of the three constituents, air, water, and solid, as well as upon the configuration or geometry of the system. Let k_a, k_w, and k_s represent the thermal conductivities of the air, water, and solid respectively. In the model the materials must be selected so that the ratios k_w/k_a and k_s/k_a are similar to the corresponding ratios for an actual sand.

The following thermal conductivity values apply to a wet sand of high quartz content at 20°C:

k_s = thermal conductivity of quartz = 20.7 $\times 10^{-3}$ cal/cm sec°C

k_w = thermal conductivity of water = 1.42 $\times 10^{-3}$ cal/cm sec°C

k_a = effective thermal conductivity of saturated air [after *Krischer*, 1941] = 0.238 $\times 10^{-3}$ cal/cm sec°C

The value for k_a is not the thermal conductivity of dry air alone, which at this temperature is 0.0615 $\times 10^{-3}$ cal/cm sec°C, but includes a term which accounts for the latent heat carried by evaporation, diffusion, and condensation of water vapor. By simulating this value of k_a in the model, the effect of evaporation and condensation upon the temperature distribution is taken into account. Thus for a wet sand, $k_w/k_a = 5.96$, and $k_s/k_a = 87.0$.

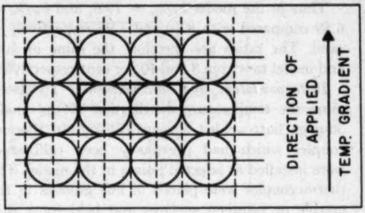

FIG. 2 – Two-dimensional representation of the open-packing arrangement simulated in the model

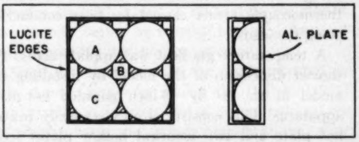

FIG. 3 – The model; A, marble hemispheres; B, silica aerogel; C, bitumen rings

The following materials were used in the model:

(1) Marble was used to represent the solid particles in the model. The four six-inch diameter white marble hemispheres were made spherical to better than $\frac{1}{64}$ inch. Two 8- by 8- by 1-inch slabs of marble were obtained from the same source, so that the thermal conductivity of the marble could be measured in an 8- by 8-inch guarded hot plate apparatus.

(2) Bitumen was chosen to represent the water in the model, since it could be shaped, without too much difficulty, into the wedge-shaped water rings around the points of contact between the solid hemispheres. The thin water films on the particle surfaces were not simulated in the model, since it was thought that they would play a minor role in determining the temperature distribution.

(3) Silica aerogel, rather than air itself, was selected to represent the air in the model to prevent convection.

The following thermal conductivity values apply to the sand model constituents at 20°C:

k_s = thermal conductivity of marble = 4.60 $\times 10^{-3}$ cal/cm sec°C

k_w = thermal conductivity of bitumen = 0.379 $\times 10^{-3}$ cal/cm sec°C

k_a = thermal conductivity of silica aerogel = 0.0576 $\times 10^{-3}$ cal/cm sec°C

Thus in the model $k_s/k_a = 79.6$, and $k_w/k_a = 6.59$ compared with 87.0 and 5.96 respectively in sand. The ratios are therefore the same in sand and model to within 8 and 10 per cent respectively.

Instrumentation and measurements—To determine the temperature distribution in the model 36-gage butt-welded chromel-constantan thermocouples which had previously been calibrated, were installed at selected points in the model. The thermocouples were placed in fine grooves in the marble or bitumen surfaces and held by a thin coat of adhesive. The thermocouples' leads were brought out along the lines of latitude of the hemispheres. Since the lines of latitude are close to being isothermal lines, this method minimizes thermocouple errors caused by heat conduction along the leads.

A temperature gradient was applied across the shorter dimension of the model by installing the model in an 18- by 18-inch guarded hot-plate apparatus. This consists of an electrically heated hot plate and two identical hollow plates (cold plates) cooled by the circulation of constant temperature liquid, and situated one on each side of the hot plate. All plates are 18 inches square. The hot plate is made in two sections, a central 12-inch square test area and an outer 3-inch wide guard ring, which are heated independently and maintained at the same temperature to minimize edge effects. A slab of 18- by 18- by 1-inch fiberboard was placed on one side of the hot plate and the model on the other. The model was installed so that it fitted exactly over the test area of the hot plate. The guard ring section was filled with fiberglass insulating material. With this arrangement, edge effects are negligible, and in addition, measurements on the effective thermal conductivity of the model could be made concurrently.

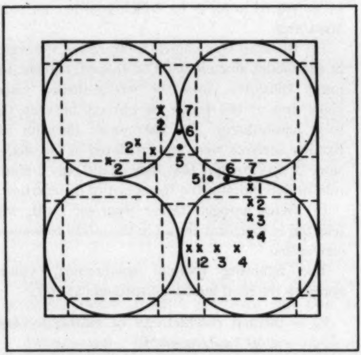

FIG. 4 – Diagram of model showing location of thermocouples; x, on marble surface; ●, on bitumen surface; 1, 2, 3, 4, θ = 30, 45, 60, 75° respectively (on spheres); 5, 6, 7, θ = 30, 60, and 90° respectively (on rings); θ = angle of latitude

The cool face of the model was kept at 55°F by circulating liquid; the hot face was maintained approximately 40°F warmer. Thermal emf's were measured relative to an ice junction with a high-precision potentiometer.

Measurements were made for two simulated 'moisture' conditions of the model. The first represented an air-dry condition, that is, water films on the particle surfaces, but no water rings at the points of contact. Thus for this condition in the model, the entire space not occupied by the marble hemispheres was filled with silica aerogel. The locations of the thermocouples are shown in Figure 4. Measured temperatures at similar positions on the two hemispheres agreed to within one per cent. At the completion of this test, the model was removed from the apparatus, re-installed and the test repeated. Reproducibility was within two per cent.

The second 'moisture' condition simulated in the model represented a moisture content of 26.6 pct by volume of saturation moisture content, or a moisture content of 12.7 pct by volume assuming the porosity to be 0.4764 (actual measured porosity of the model = 0.4711). This 'moisture content' corresponded to bitumen 'water' rings of two-inch radius at the points of contact between hemispheres. No attempt was made to simulate the meniscus curvature of the 'water' rings. The locations of the thermocouples are shown in Figure 4.

Results—From the emf developed by each thermocouple, a temperature corresponding to each thermocouple position was determined. Taking into account the symmetry, the temperature differences between mirror image points separated by the air gap were calculated. The average temperature gradient between any two such points was assumed to be that obtained by dividing the temperature difference by the distance between the points.

The temperature difference between the two isothermal metal plates divided by the distance between them is equal to the over-all gradient. For the different angles of latitude the ratio F of the gradient between mirror image points on the surface of the solid to the over-all gradient was calculated. These are shown in Figure 5a for the

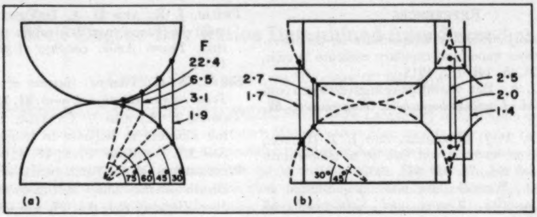

FIG. 5 – Values of the ratio F for (a) the system solid and air; (b) the system solid, air, and water

system solid and air, and in Figure 5b for the system solid, air, and water.

Since the magnitude of F changes with angle of latitude, an average value of F is desirable. Figure 5a shows the value of the factor F at angles of latitude of $\theta = 30$, 45, 60, and 75° for the system solid and air. The value of F at $\theta = 15°$ was interpolated from a graph of F vs θ ($F = 1$ at $\theta = 0$). The average value of F, between $\theta = 7.5°$ and 82.5°, taking account of the slope of spherical surface, and assuming linear flow of heat in the pore spaces, was calculated as

$$\overline{F} = \frac{\frac{\pi}{12}\sum_{i=1}^{5} F_i \cos\theta_i \sin\theta_i}{\int_{\pi/24}^{11\pi/24} \cos\theta \sin\theta \, d\theta} = 6.02$$

where $\theta_i = 15$, 30, 45, 60, and 75°, and F_i are the corresponding values of F. No suitable averaging method could be found for determining $\overline{F}$ for the system solid, air, and water.

Discussion—For the system solid and air, the average value of F is 6, that is, the average temperature gradient across the pore space is six times the over-all gradient. It follows therefore that approximately this same ratio exists between the respective vapor pressure gradients. For the system solid, air, and water, the average value of F was not calculated, but a consideration of the values of F in Figure 5b indicates that the average would be less than six. As the moisture content of the system decreases from 26 pct toward zero, the average value of F will approach 6.

It is therefore proposed that the mechanism of movement involves multiple vapor diffusion and liquid flow steps in series. The resistance to flow in the liquid phase is considered negligible (at least at high relative humidities) so that the rate of moisture transfer is determined by the rate of vapor diffusion. Consequently, if the correct vapor pressure gradient is used in calculating the rate of flow, much better agreement between observed and calculated rates may be expected.

After the completion of the work reported in this paper, a paper by *Philip* and *DeVries* [1957] was brought to the attention of the present authors in which, from theoretical considerations, they arrived at the same general conclusion as reported in this paper regarding the mechanism of moisture flow through a porous material subjected to a temperature gradient. Theoretical values of $\overline{F}$ (denoted by ζ) were tabulated for different porosities and moisture contents. These values ranged between 1.3 and 3.2. If the Philip and DeVries method [*DeVries*, 1952] for calculating $\overline{F}$ is used, a value of 2.04 is obtained for the air-dry condition of the model, compared with the above measured value of 6.02. The Maxwell-Burger-Eucken theory, on which the Philip and DeVries method is based, assumes that the distances between particles are large compared with the particle size. Now, if one makes the approximation that the granular material may be represented by an air layer and a solid layer in series, $\overline{F}$ is found to be 2.09 for the porosity and conductivity ratio used in the model. The fact that the value obtained making this very rough approximation is similar to that calculated by the Philip and DeVries method indicates that the Maxwell-Burger-Eucken theory, because of the assumption concerning the distances between particles, is not applicable to most granular materials.

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Snow-Melt Degree-Day Ratios Determined from Snow-Lab Data

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Abstract—Observations made at the Central Sierra Snow Laboratory in California and the Upper Columbia Snow Laboratory in western Montana have been used to determine the ratio of the amount of snow melt to the accumulated number of degree days or degree hours above selected base temperatures during the late spring melting season. The use of degree days was found to give smaller errors of estimation than degree hours, and a base temperature of 32°F gave smaller errors of estimation than other bases tried. The ratio was found to be smaller for greater forest cover and to increase during the melting season. No relation was found between the ratio and average wind, humidity, or cloudiness. These, of course, have important physical effects on the heat supply to a snow cover, but variations in their effect could be obscured by the fact that they were averaged over weekly or longer periods, and some of their effect may be included in the time-of-year parameter.

Introduction—The average air temperature during a melting period can be considered an index of the integrated effect of radiation, and sensible heat exchange. If it is assumed that negligible snow melting will occur when the air temperature is below some certain value, this value can be chosen as a base temperature and the difference between the observed air temperature and the base can be used as an index of the heat available for melting. When hourly temperatures are used and differences summed for the melting period, the total is called degree hours for the period. When mean daily temperatures are used the summed differences are called degree days. In this study, mean daily temperature is the sum of the recorded daily maximum and minimum divided by two.

It is the purpose of this paper to report the empirical relations between the accumulated degree days (or degree hours) and the concomitant snow melt, as determined from the data in the *Hydrometeorological Logs* of the Cooperative Snow Investigations of the Corps of Engineers and the Weather Bureau. These logs constitute a unique set of carefully observed integrated data from which to determine such relations. Reference to these logs may be made for heights of instruments, descriptions of snow and temperature sites, occurrence of snow cover at time of temperature observations, etc. Data for selected stations in the Central Sierra Snow Laboratory (CSSL) in California for the snow melting season (April–June) of the years 1947–52 and in the Upper Columbia Snow Laboratory (UCSL) in western Montana for the snow melting season (April–June) of the years 1947–50 were chosen. The selection was made to provide examples for different station-site conditions of exposure and forest cover, with consistent and uniform coverage of data. Temperatures at stations 1 and 1b were recorded at four feet above the snow or ground surface; at site stations this height varied considerably, but averaged about ten feet above the ground.

Daily changes in water equivalent of the snow pack during the melting season frequently amount to about an inch. Single point observations of snow-pack water equivalent may have sampling and instrumental errors of about an inch (standard error). These errors obscure the empirical relationship when daily changes are used. Because of this, selected periods used were usually weekly, occasionally biweekly or monthly, in order to permit the increment of change in snow-pack water equivalent to greatly exceed its observational error, and the error inherent in making corrections for rainfall.

Method of analysis of the data—The analysis consisted of plotting the change in water equivalent of the snow pack (adjusted for any rainfall during the period) versus the degree days (or degree hours) for the same time period on arithmetic cross-section paper and fitting an estimated line of best fit to the points by inspection. The slope of this line is called the degree-day (or degree-hour) ratio, and represents the inches of melt (water equivalent) per degree day (or degree hour).

The ratios were determined using different base temperatures. The magnitude of the standard error of estimate of snow melt divided by the mean of the snow-melt values for all the periods was used as a basis of comparison of the ratios. About twenty periods were available for the determination of each ratio. Tests indicated that the relations were not improved by including the effect of negative degree hours. There were too few negative degree days for an adequate test.

To illustrate the relation of the ratio magnitude

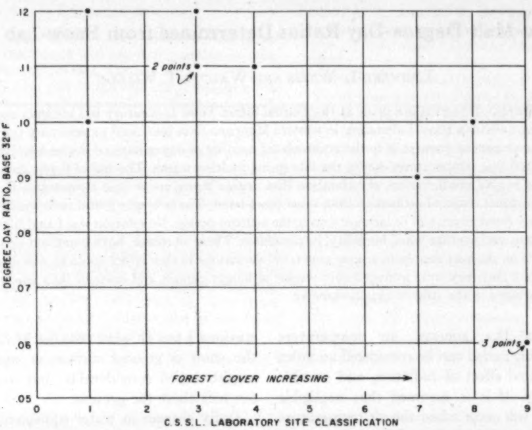

FIG. 1 - Illustrating the decrease of degree-day ratio with increase of forest cover

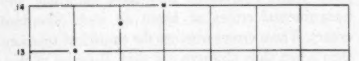

FIG. 2 - Illustrating the decrease of degree-day ratio with increase of forest cover

to the amount of forest cover, the ratios for a base temperature of 32°F were plotted versus the laboratory-site classification number and are shown in Figures 1 and 2. The site classifications are given in Tables 1 and 2 and represent a measure of forest cover. Ratios were plotted versus average dew point, average cloudiness, and average wind speed for the period, but no relationship was detected.

To determine whether the ratio varied with the time of year within the melting season, the ratio values for each melting period (usually about seven days) were assigned the date of the mid-point in the period. Only those periods were used where the incremental change was two inches or more. The season was then divided into ten-day intervals starting April 1. All the ratios for a given station whose mid-date fell within the ten-day interval were averaged. These average ratios were then plotted versus time of year and fitted by inspection with straight lines. Examples are shown in Figures 3 and 4.

Results of the analysis—The ratios determined by using different base temperatures are compared in Tables 1–5. The use of a base temperature of 32°F is seen to give the smallest average standard error in per cent of the mean. Over the range of station elevations in CSSL the difference in the ratios determined from temperature observations at the melting site or at another station are too small to be of practical consequence. However, in UCSL where the differences in station elevation can exceed a thousand feet, a temperature adjustment may be necessary when the temperatures are observed at a station other than the melting site. For this adjustment an average decrease of temper-

TABLE 1 — *Degree-day ratios (inches melt, water equivalent, per degree day) for daily mean temperature, Central Sierra Snow Laboratory, 1947–1952*

Station	Base 28°F Site Sta		Base 28°F Sta 1		Base 30°F Sta 1		Base 32°F Sta 1		Base 35°F Sta 1		Remarks		
	Deg-day ratio	c	Deg-day ratio	c	Deg-day ratio	c	Deg-day ratio	c	Deg-day ratio	c	a	b	Elev
													ft
3	0.110	21	0.095	29	0.101	29	0.120	15	0.160	27	SW	(1)	7170
4	0.083	35	0.065	28	0.083	32	0.109	25	0.148	43	SW	(3)	7245
5	0.087	24	0.075	26	0.091	26	0.109	19	0.146	24	SE	(4)	7370
7	..	..	..	..	..	..	0.100	22	..	..	S	(8)	7170
9	0.079	36	0.073	32	0.085	31	0.102	28	0.152	38	S	(1)	7510
12	0.078	33	0.078	18	0.093	21	0.109	27	0.150	29	N	(3)	7550
14	..	..	..	..	..	..	0.120	25	..	..	S	(3)	7480
16	0.051	33	0.048	28	0.054	35	0.065	26	0.081	32	E	(9)	7510
19	..	..	..	..	..	..	0.089	31	..	..	S	(7)	7340
33	..	..	..	..	..	..	0.062	42	..	..	SE	(9)	7440
34	..	..	..	..	..	..	0.061	48	..	..	SW	(9)	7040
Aver. of Sta 3, 4, 5, 9, 12 and 16	0.081	29	0.072	27	0.084	29	0.095	23	0.140	32			

a Station exposure dominant direction

b Laboratory site classifications (with reference to forest cover):

(1) Distant (over 100 ft) from forest margin; ground clear.
(3) Distant (over 100 ft) from forest margin; scattered trees.
(4) Distant (over 100 ft) from forest margin; thickets and scattered trees.
(7) Near (100 ft) from forest margin; scattered trees.
(8) Near (100 ft) from forest margin; thickets and scattered trees.
(9) Within forest.

c Standard error/mean in per cent.

TABLE 2 – *Degree-day ratios (inches melt, water equivalent, per degree day) for daily mean temperature, Upper Columbia Snow Laboratory, 1947–1950*

Station	Base 30°F Sta 1b		Base 32°F Sta 1b		Base 32°F Sta 1b		Base 34°F Sta 1b		Base 32°F Site Sta		Remarks		
	Deg-day ratio	c	Deg-day ratio	c	Deg-day ratio d	cd	Deg-day ratio	c	Deg-day ratio	c	a	b	Elev
													ft
2	0.061	47	0.079	44	0.079	44	0.098	49	..	..	W	(2)	4825
6B	0.058	37	0.074	26	0.118	32	0.090	19	..	..	SW	(3)	6315
10	0.060	53	0.067	43	0.116	38	0.079	46	0.099	38	W	(3)	6340
11	0.062	54	0.079	44	0.124	26	0.098	36	..	..	W	(4)	5780
12	0.054	65	0.065	60	0.080	62	0.080	62	0.090	51	W	(4)	5300
13	0.078	44	0.104	45	0.140	61	0.140	61	..	..	W	(3)	5300
15	0.064	45	0.080	43	0.084	41	0.089	43	..	..	W	(3)	5250
16	0.048	41	0.058	41	0.063	38	0.067	43	..	..	..	(7)	5150
17	0.043	48	0.050	40	0.059	43	0.059	43	..	..	N	(7)	5500
18	0.063	45	0.078	45	0.115	46	0.095	45	..	..	S, NW	(3)	5860
19	0.071	34	0.085	26	0.130	23	0.108	24	..	..	S, NW	(1)	5900
20	0.060	52	0.077	44	0.111	52	0.097	48	..	..	N	(3)	5950
22	0.064	53	0.079	53	0.136	50	0.099	50	..	..	N	(2)	6050
Aver. value	0.060	48	0.075	43	0.103	43	0.092	44					

a Station exposure dominant direction.

b Laboratory site classifications (with reference to forest cover):

(1) In area of scattered trees and small groves.
(2) In clearing or near margin of forest of low trees (under 30 ft).
(3) In clearing or near margin of forest of medium trees (30–50 ft).
(4) In clearing or near margin of forest of tall trees (over 50 ft).
(7) In clearing or near margin of forest of tall trees.

c Standard error/mean in per cent.

d Adjusted for elevation.

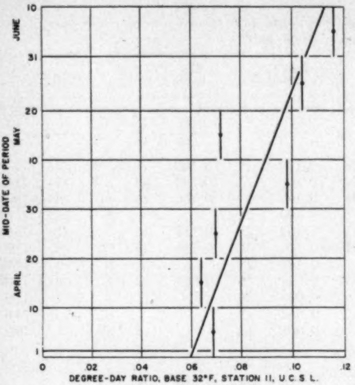

FIG. 3 – Example of degree-day ratios averaged by ten day intervals showing change during the melting season

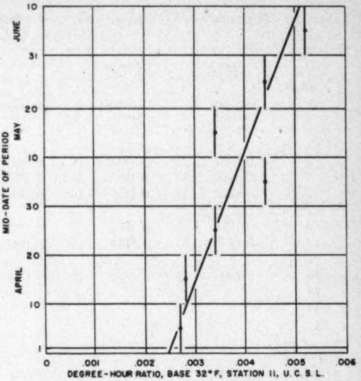

FIG. 4 – Example of degree-hour ratios averaged by ten day intervals showing change during the melting season

TABLE 3 – *Degree-hour ratios (inches melt, water equivalent, per degree hour) for daily mean temperature, Central Sierra Snow Laboratory, 1947–1952*

Station	Base 28°F Sta 1		Base 30°F Sta 1		Base 32°F Sta 1		Base 34°F Sta 1		Base 36°F Sta 1	
	deg-hr ratio	a	Deg-hr ratio	a	Deg-hr ratio	a	Deg-hr ratio	a	Deg-hr ratio	a
3	0.004	22	0.004	22	0.005	16	0.006	23	0.007	24
4	0.003	39	0.004	36	0.005	36	0.005	45	0.006	49
5	0.003	26	0.004	21	0.004	24	0.005	24	0.006	26
9	0.003	28	0.004	28	0.005	28	0.005	31	0.006	28
12	0.003	33	0.004	31	0.004	26	0.005	28	0.007	32
16	0.002	54	0.002	52	0.003	45	0.003	48	0.004	48
Aver. value	0.003	34	0.004	32	0.004	29	0.005	33	0.006	35

a Standard error/mean in per cent.

TABLE 4 – *Degree-day ratios (inches melt, water equivalent, per degree day) for daily maximum temperature, Central Sierra Snow Laboratory, 1947–1952*

Station	Base 32°F Sta 1		Base 35°F Sta 1		Base 37°F Sta 1		Base 40°F Sta 1		Base 45°F Sta 1	
	Deg-day ratio	a	Deg-day ratio	a	Deg-day ratio	a	Deg-day ratio	a	Deg-day ratio	a
3	0.048	41	0.060	24	0.066	31	0.077	27	0.112	40
4	0.040	42	0.045	31	0.052	29	0.061	36	0.085	57
5	0.043	32	0.051	31	0.056	29	0.066	26	0.091	29
9	0.039	37	0.048	28	0.052	33	0.063	36	0.083	34
12	0.043	25	0.053	28	0.052	29	0.070	26	0.095	28
16	0.028	55	0.028	60	0.032	52	0.037	45	0.054	37
Aver. value	0.040	39	0.048	34	0.052	34	0.062	33	0.087	38

a Standard error/mean in per cent.

ature with increase of station elevation of about three degrees per thousand feet has been suggested by other investigators. We have found this value to be satisfactory for the spring melting season

Table 5 – *Degree-hour ratios (inches melt, water equivalent, per degree-hour) for daily mean temperature, Upper Columbia Snow Laboratory, 1947–1950*

Station	Base 30°F Sta 1b		Base 32°F Sta 1b		Base 34°F Sta 1b	
	Deg-hour ratio	a	Deg-hour ratio	a	Deg-hour ratio	a
2	0.003	49	0.004	54	0.004	54
6B	..	..	0.003	34	..	..
10	..	..	0.004	44	..	..
11	0.003	57	0.003	50	0.004	43
12	0.002	83	0.002	79	0.003	82
13	0.004	30	0.004	29	0.006	39
15	0.003	60	0.003	57	0.004	57
16	..	..	0.003	36	..	..
17	..	..	0.002	48	..	..
18	..	..	0.004	45	..	..
19	..	..	0.004	45	..	..
20	..	..	0.003	44	..	..
22	..	..	0.004	45	..	..
Aver. value Sta 2, 11, 12, 13 and 15	0.003	56	0.003	54	0.004	55
Aver. value, all	..	..	0.003	47	..	..

a Standard error/mean in per cent.

Table 6 – *Degree-day ratios (inches melt, water equivalent, per degree-day) for daily mean temperature at Sta 1b, Upper Columbia Snow Laboratory, 1947–1950*

Station	Base 40°F Sta 1b	
	Deg-day ratio	a
2	0.059	47
6B	0.060	31
10	0.055	68
11	0.055	47
12	0.044	65
13	0.080	37
15	0.057	41
16	0.042	42
17	0.037	45
18	0.060	49
19	0.066	29
20	0.058	54
22	0.064	53
Aver. value	0.057	47

a Standard error/mean in per cent.

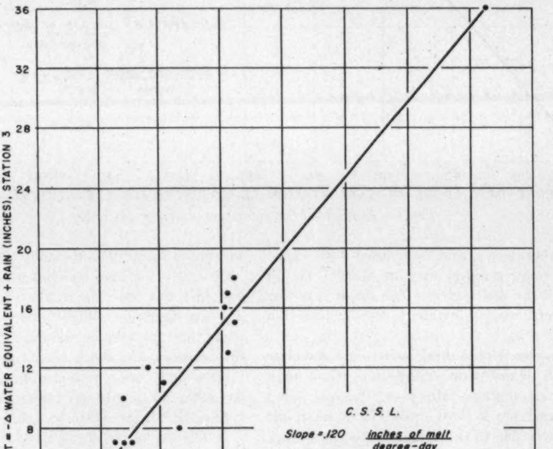

Fig. 5 – Example of determination of degree-day ratio

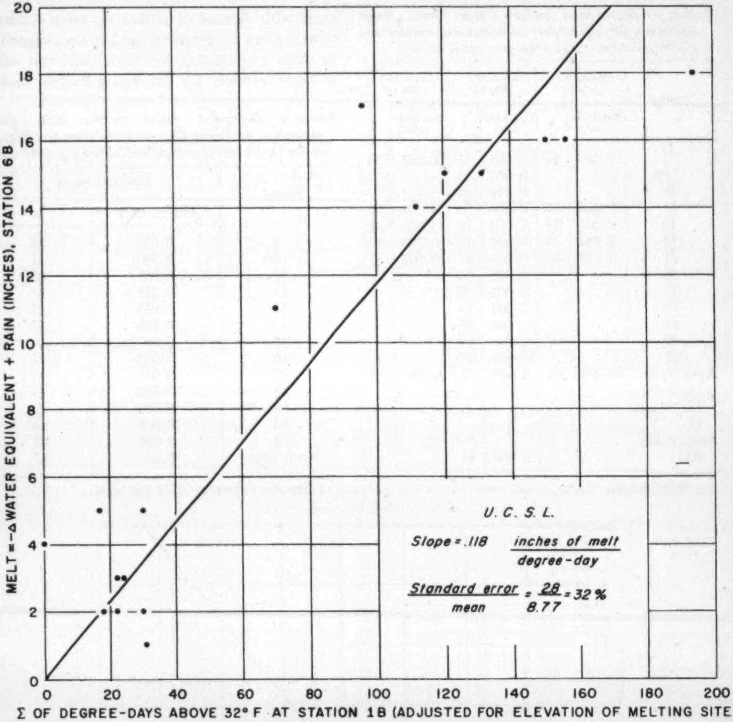

FIG. 6 – Example of determination of degree-day ratio

in these laboratories, and have used it to adjust the daily mean temperatures at station 1b for elevation of the melting site. The ratios resulting from use of these adjustments are included in Table 2.

It was expected that total melt would correlate better with degree-hour summations than with degree-day summations. However, this was found on the average not to be the case. That this result was not solely due to using long periods was supported by a comparison of the scatter diagrams of degree days above 32°F and degree hours above 32°F versus the daily streamflow at Castle Creek (CSSL). The scatter was large but was less for degree days than for degree hours.

Degree-day ratio determinations using the daily maximum rather than the daily mean temperature were made for base temperatures of 35, 37, 40, and 45°F in CSSL. The results are shown in Table 4. Forty degrees was slightly better than the other bases, but the average standard error in per cent of the mean was about 50 pct greater than that for the daily mean temperature method. Degree-day ratios for base 40 and daily maximum temperature in UCSL are shown in Table 6.

A decrease of the degree-day ratio was expected with increase in forest cover. Figures 1 and 2 show the ratios in terms of forest cover as indicated by the laboratory-site classifications. These classifications are somewhat arbitrary, do not increase in linear fashion and are different for the two laboratories. But the figures indicate the important

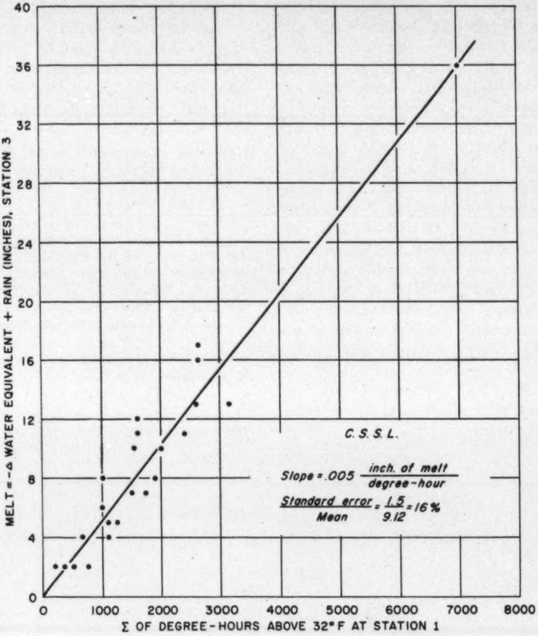

FIG. 7 – Example of determination of degree-hour ratio

influence of forest cover in decreasing the melting rate. For stations in forest the season-mean degree-day ratio of about 0.06 is indicated; for open sites about 0.12 and for intermediate locations about 0.09. In Figure 2 (UCSL) the ratios used were those adjusted for elevation difference between the temperature site and the melting site.

A variation of ratio magnitude with time of year within the melting season was found such that the mean values as given in the tables apply to early May and vary from 0.7 of the mean value for early April to 1.3 times the mean value for early June.

Discussion—The points which determine the ratio show considerably greater scatter for UCSL stations than for CSSL stations. This is probably because CSSL has less variability of air masses, and less advective change. At UCSL the topography is more rugged with air occasionally spilling over the continental divide from the east giving greater variability in temperature and humidity. Also there is greater probability of change in albedo of the snow at UCSL because of intermittent snow late in the season, with alternations of new and old snow being exposed to the sun.

It has been observed that the total storage of liquid water in a snow pack seldom exceeds five per cent of the water equivalent of the pack. Changes, during the melting periods studied, in the small liquid component of the water equivalent of the pack are believed to be negligibly small compared with the change in total water equivalent over the same periods.

During the progress of the melting season, the average dew point and average incident radiation for the melting periods gradually increases, the the average cloudiness decreases. Even though no relations between the ratios and these individual parameters were detected, their combined influence may be included in the time-of-year parameter which does show a relationship.

The degree-day ratios give estimates for (generally) weekly periods with standard error of less than 30 pct of the mean as indicated by the dependent data of the scatter diagrams. The correlations were all above 0.80. For shorter time intervals, poorer correlations would be expected.

Sample scatter diagrams showing determination of degree-day ratios are shown in Figure 5 for CSSL and in Figure 6 for UCSL. One showing degree-hour ratio is shown in Figure 7 for CSSL. The rain adjustments added to the change in water equivalent were measured at Stations 1 or 1b.

Conclusions—The following conclusions are drawn. (1) The use of degree-day summations based on daily mean temperature gave smaller errors of estimate of concomitant snow melt than degree-hour summations; and both were superior to the use of summations based on daily maximum temperature.

(2) The use of a temperature base of 32°F gave the smallest standard error of estimate in per cent of the mean.

(3) The season-mean degree-day ratio for sites within forest was 0.06 inches snow melt per degree day; for sites in the open 0.12, and for intermediate sites about 0.09. This mean value applies to early May. For early April the values were 0.04, 0.08, and 0.06 respectively. For early June they were 0.08, 0.16, and 0.12 respectively.

(4) The degree-day ratio was as satisfactory for estimating snow melt in open and windy locations as at forest sites.

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Two-Dimensional Gravity Drainage Profiles

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Abstract—This paper concerns some studies made on the shape of the fluid-fluid interface of a liquid which is draining by gravity from a saturated porous medium. The first part is a review of the classical potential theory solution by *Hamel* and *Gunther* [1935]. This solution is then put into a form amenable to solution by a digital computer and some discussion of the numerical methods employed is given. The results of a series of numerical solutions are used to define an area function which is employed along with the mass balance concept and the idea of a succession of steady states to derive an expression for transient drainage from a two dimensional saturated medium. This transient solution is compared with the actual drainage rate from a Hele-Shaw analog system.

Introduction—This paper concerns some studies made in our laboratory on the shape of the free surface, that is, the fluid-fluid interface, of a liquid which is draining by gravity from a saturated porous medium. Both analytic and experimental results are discussed. Our studies were confined to two dimensional flow problems. The classical physical analogy is that of seepage through a dam with vertical faces. References to previous work on this problem are given by *Muskat* [1946] whose Chapter 6 on gravity-flow systems is probably the most pertinent single reference.

The first part of this paper is a review of the classical potential theory solution by *Hamel* and *Gunther* [1935]. This solution is then put into a form amenable to solution by a digital computer and some discussion of the numerical methods employed is given. The results of a series of numerical solutions are used to define an area function which is employed along with the mass balance concept and the idea of a succession of steady states to derive an expression for transient drainage from a two dimensional saturated medium. This transient solution is compared with the actual drainage rate from a Hele-Shaw analog system.

Description of the problem—We are concerned with the system sketched in Figure 1, using the notation of *Muskat* [1946, p. 303]. Only the case where the downstream liquid level is zero is considered. Analytical solutions will give the coordinates of the free surface and the dimensions h and L in terms of a system parameter $\bar{k}$ and a mapping parameter b. The system parameter is defined by the equation in the dimension of length

$$k = k\gamma g/\mu \tag{1}$$

where

γ is fluid density
μ is dynamic viscosity
g is acceleration of gravity
k is the permeability defined by the Darcy equation

$$v = -k(\gamma/\mu)\,\mathrm{grad}\,\phi \tag{2}$$

in which v is the fluid velocity vector, and ϕ is the potential function, $gZ + (p - p_0)/\rho$, p being pressure. These are familiar expressions. The mapping parameter b is defined in the next section.

Analytical solution—To review the solution of *Hamel* and *Gunther* [1935], the hodograph of Figure 1 is shown in Figure 2, and β makes its appearance. This is now mapped to what Hamel calls the $\underline{q}$ plane by the mapping function $q = i(u - iv)/k$ to obtain Figure 3. This may finally be transformed to a single straight line by the mapping function

$$\lambda = [\Theta(q) - 1]/\Theta(q) \tag{3}$$

where $\Theta(q) = K^2$ is the modular elliptic function of modulus K defined by the relations

$$\Theta(0) = 1, \quad \Theta(1) = \infty$$
$$\Theta(i^{\infty}) = \Theta(1 + i^{\infty}) = 0$$

The original boundary conditions of the problem, which may be stated in terms of a complex velocity potential $\phi(Z)$ are not easily carried through these transformations but an intermediate potential function defined by the relation

$$\theta - i\tau = i \log\,[-d^2\phi/dZ^2] \tag{4}$$

has the boundary values of its real part specified in each transformation. The values of θ in the final transformation are shown in Figure 4 [Muskat, 1946, Fig. 101]. Since values of θ are known along the whole real axis and the upper half plane represents the flow region, this last transformation formally solves the problem. The value of $\theta - i\tau$ in the upper half plane is given by

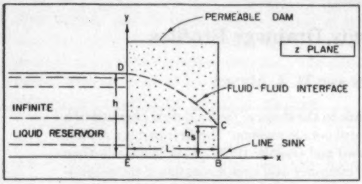

FIG. 1 – Sketch of the system

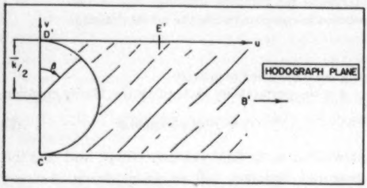

FIG. 2 – Hodograph of Figure 1

$$\theta - i\tau = i\tau_0 + \frac{1}{\Pi i}\int_{-\infty}^{+\infty} \frac{\theta(\epsilon)(\lambda\epsilon + 1)\,d\epsilon}{(\epsilon - \lambda)(1 + \epsilon^2)}$$

where τ_0 is an arbitrary constant [*Muskat*, 1946, p. 308.]

Note that there is only one unspecified parameter in Figure 4, namely, the real coordinate b of the point E'''. Therefore it should be possible to let b vary between the limits 1 and $+\infty$ to determine solutions for all two dimensional problems similar to that shown in Figure 1 in which the ratio L/h lies between 0 and $+\infty$. The subsequent section on ***Numerical evaluation*** shows the difficulty of applying this theory.

Integral equation solutions—Using the identity $dZ = d[\phi(Z)]/\phi''(Z)$ (primes indicate differentiation), we have

$$Z = -\int \frac{d(u + iv)}{\phi''(Z)} = \int e^{\tau + i\theta}\, d(u + iv) \quad (5)$$

having used the definition of τ and θ in (4) and the definition of the complex potential function. Since θ assumes constant values along segments of the real axis in Figure 4, (5) may be integrated along this line which is the free surface in the physical plane to give pertinent expressions. For example, integrating from E to B, where $\theta = 0$ gives an expression for the length L measured through the dam

$$L = \int_{u(E)}^{u(B)} e^{\tau} du \quad (6)$$

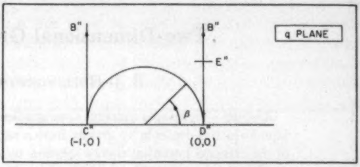

FIG. 3 – Mapping in the q plane

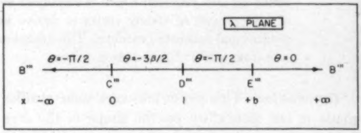

FIG. 4 – Final transformation of θ values

Similarly

$$h = \int_{u(E)}^{0} e^{\tau} du \quad (7)$$

and

$$h_s = \int_{u(B)}^{0} e^{\tau}\, du = -\int_{\infty}^{0} e^{\tau}\, du \quad (8)$$

The coordinates of the free surface involve the parameter β

$$x - L + i(y - h_s) = (k/2)\int_{\Pi}^{\beta} \exp\,(\tau - i\beta/2)\, d\beta \quad (9)$$

Eqs. (6) to (9) are deceptively simple since the functional relationships between the variables are complicated. The following identities and definitions may be used to derive integral expressions amenable to machine solution.

Let $f(K^2)$ be the inverse of the modular elliptic function such that if $\Theta(q) = K^2$, then $iq = -f(K^2)$.

This inverse function is tabulated by *Hayashi* [1930] to ten decimal places. It is closely approximated by the expression

$$iq \simeq \frac{1}{\Pi}\left(\ln \frac{K^2}{16} + \frac{K^2}{2} + \frac{13K^4}{64} + 0.889893\right) K^6 + 0.1958056\, K^8$$

whenever $K^2 \leq \frac{1}{2}$ and by $iq = 1/ - f(1 - k^2)$ whenever $\frac{1}{2} < K^2 \leq 1$. From the geometry of the mapping

$$\left.\begin{aligned}\tan \beta/2 &= f(\lambda)\\ \sin \beta/2 &= f(\lambda)/[1+f^2(\lambda)]^{\frac{1}{2}}\\ \cos \beta/2 &= 1/[1+f^2(\lambda)]^{\frac{1}{2}}\end{aligned}\right\} \qquad (10)$$

$$d\beta = 2d\, f(\lambda)/[1+f^2(\lambda)]$$

Except on the circular arc of the q-plane we have

$$dv = 0 \qquad (11)$$

Relations (10) and (11) allow us to write (6) to (8) in terms of a single variable λ.

$$L = \bar{k} \int_b^\infty \left[\frac{\lambda - 1}{\lambda(\lambda - b)}\right]^{\frac{1}{2}} e^\alpha \, df(1/\lambda) \qquad (12)$$

$$h_s = -\bar{k} \int_{-\infty}^0 \left[\frac{1 - \lambda}{\lambda(\lambda - b)}\right]^{\frac{1}{2}} e^\alpha \, df(1/1 - \lambda) \qquad (13)$$

$$x - L = \bar{k} \int_0^{\lambda \le 1} \left[\frac{\lambda - 1}{\lambda(\lambda - b)}\right]^{\frac{1}{2}} e^\alpha \frac{df(\lambda)}{[1 + f^2(\lambda)]^{\frac{3}{2}}} \qquad (14)$$

$$y - h = -k \int^{\lambda \le 1} \left[\frac{\lambda - 1}{\lambda(\lambda - b)}\right]^{\frac{1}{2}} e^\alpha \frac{f(\lambda)\, df(\lambda)}{[1 + f^2(\lambda)]^{\frac{3}{2}}} \qquad (15)$$

where

$$\alpha(\lambda) = -\frac{3}{\Pi} \int_0^1 \frac{\tan^{-1} f(t)}{t - \lambda}\, dt$$

These equations are in a convenient form for evaluation by a digital computer.

Numerical evaluation of the integrals—Hamel and *Gunther* [1935] give a table of α in the range, $-20 \le \lambda \le 20$. Since this table was too abbreviated for our work, the integral was evaluated as shown below. For $0 < \lambda < 1$

$$\begin{aligned}\alpha &= -\frac{3}{\Pi} \int_0^1 \frac{\tan^{-1} f(t)\, dt}{t - \lambda}\\ &= -\frac{3}{\Pi}\left[\int_0^1 \frac{\tan^{-1} f(t) - \tan^{-1} f(\lambda)}{t - \lambda}\right.\\ &\qquad\qquad \left. + \tan^{-1} f(\lambda) \left\{\ln \frac{1-\lambda}{\lambda}\right\}\right]\\ &\simeq -\frac{3}{\Pi}\left[\sum_{i=1}^{8} \cdot R_i \frac{\tan^{-1} f(\mu_i + \frac{1}{2}) - \tan^{-1} f(\lambda)}{u + \frac{1}{2} - \lambda}\right.\\ &\qquad\qquad \left. + \tan^{-1} f(\lambda) \left\{\ln \frac{1-\lambda}{\lambda}\right\}\right]\end{aligned}$$

in which the R_i and μ_i are respectively the weight factors and point coordinates defined by the Gauss quadrature method using eight points [*Scarborough*, 1950, sec. 49].

When $|\mu_i + \frac{1}{2} - \lambda| \le 0.005$, the factor

$$\frac{\tan^{-1} f(\mu_i + \frac{1}{2}) - \tan^{-1} f(\lambda)}{\mu_i + \frac{1}{2} - \lambda}$$

is replaced by its limit as $|\mu_i + \frac{1}{2} - \lambda|$ approaches zero

$$\left[\frac{df(\lambda)}{d\lambda}\right] \Big/ [1 + f(\lambda)]$$

For λ outside the interval (0, 1)

$$\alpha(\lambda) \simeq -\frac{3}{\Pi} \sum_{i=1}^{8} R_i \frac{\tan^{-1} f(\mu_i + \frac{1}{2})}{\mu_i + \frac{1}{2} - \lambda}$$

Eq. (12) and (13) have such critical singularities that the Gauss quadrature method may not be directly applied. A brute-force method of series expansion was used as indicated below

$$\begin{aligned}\frac{L}{\bar{k}} &= \int_l^\infty F(\lambda) = \int_b^{b+\epsilon} + \int_{b+\epsilon}^\infty\\ &= \int_{b+\epsilon/10}^{b+\epsilon} + \int_{b+\epsilon/100}^{b+\epsilon/10} + \int_{b+\epsilon/1000}^{b+\epsilon/100} + \cdots\\ &\qquad + \int_{b+\epsilon}^{2(b+\epsilon)} + \int_{2(b+\epsilon)}^{4(b+\epsilon)} + \int_{4(b+\epsilon)}^{16(b+\epsilon)} + \cdots \qquad (12')\end{aligned}$$

$$\begin{aligned}\frac{h_s}{\bar{k}} &= \int_{-\infty}^0 G(\lambda) = \int_{-2}^0 + \int_{-\infty}^{-2}\\ &= \int_{-2}^{-\frac{1}{2}} + \int_{-\frac{1}{2}}^{-\frac{1}{4}} + \int_{-\frac{1}{4}}^{-\frac{1}{16}} + \cdots\\ &\qquad + \int_{-4}^{-2} + \int_{-16}^{-4} + \int_{-256}^{-16} + \cdots \qquad (13')\end{aligned}$$

The integral terms in each series expansion were evaluated by the four point Gauss quadrature method until their contributions became negligible.

Twelve sets of coordinate points x_i, y_i were computed by (14) and (15) along the interface for each value of b using

$$\frac{x_i - L}{\bar{k}} = \int_0^{\lambda_i} H(\lambda), \qquad \frac{y_i - h}{\bar{k}} = \int_0^{\lambda_i} I(\lambda)$$

The values chosen for λ_i were $\lambda_1 = 0.5$, $\lambda_2 = 0.9$, 0.96, 0.975, 0.988, 0.994, 0.997, 0.9985, 0.9993, 0.9999, and $\lambda_{12} = 1.0$. Obviously x_{12} should equal zero, this was used to check the numerical integration.

As mentioned in *Analytical solutions*, it should be possible, by selecting values of b between the limits of 1.0 and ∞ to obtain solutions for any problems of the type sketched in Figure 1. *Muskat* [1946, p. 314] presents four solutions from b = 1.2 to 10.0 which show an encouraging variation. However as we found on evaluating the integrals that for thin dams ($L < h/3$) the values of b must

TABLE 1 – *Profile coordinates*

$b = 1.0000001$ $L = 11.88$ $h = 0.731$		$b = 1.0001$ $L = 7.69$ $h = 0.731$		$b = 1.001$ $L = 5.62$ $h = 0.731$		$b = 1.01$ $L = 3.74$ $h = 0.729$		$b = 1.1$ $L = 2.04$ $h = 0.717$		$b = 1.2$ $L = 1.63$ $h = 0.704$	
x	y	x	y	x	y	x	y	x	y	x	y
0	4.83	0	3.92	0	3.35	0	2.72	0	2.01	0	1.79
3.23	4.18	0.46	3.82	0.16	3.33	0.11	2.71	0.02	2.01	0.01	1.78
5.40	3.66	1.55	3.56	0.56	3.23	0.24	2.67	0.06	2.00	0.04	1.78
7.25	3.13	3.11	3.11	1.41	2.98	0.55	2.58	0.16	1.97	0.11	1.76
7.93	2.91	3.76	2.90	1.90	2.82	0.76	2.51	0.23	1.94	0.16	1.74
8.53	2.69	4.34	2.69	2.39	2.65	1.01	2.43	0.32	1.91	0.22	1.72
9.08	2.49	4.89	2.48	2.89	2.46	1.31	2.31	0.43	1.87	0.30	1.69
9.60	2.27	5.41	2.27	3.38	2.26	1.66	2.16	0.57	1.81	0.41	1.64
10.11	2.04	5.91	2.04	3.87	2.03	2.06	1.98	0.77	1.72	0.55	1.58
10.40	1.89	6.20	1.89	4.16	1.88	2.32	1.85	0.91	1.65	0.66	1.52
10.92	1.59	6.72	1.59	4.67	1.59	2.80	1.58	1.23	1.46	0.91	1.38
11.64	1.04	7.45	1.04	5.39	1.04	3.50	1.04	1.82	1.01	1.42	0.98

$b = 2.0$ $L = 0.940$ $h = 0.626$		$b = 5.0$ $L = 0.491$ $h = 0..499$		$b = 10$ $L = 0.327$ $h = 0.411$		$b = 20$ $L = 0.221$ $h = 0.333$		$b = 80$ $L = 0.107$ $h = 0.207$	
x	y	x	y	x	y	x	y	x	y
0	1.23	0	0.832	0	0.638	0	0.490	0	0.284
0.384	1.07	0.192	0.753	0.128	0.586	0.088	0.454	0.046	0.267
0.503	0.99	0.255	0.710	0.171	0.557	0.118	0.435	0.060	0.257
0.581	0.93	0.297	0.677	0.200	0.535	0.138	0.419	0.070	0.249
0.641	0.87	0.331	0.648	0.222	0.515	0.153	0.405	0.078	0.243
0.689	0.83	0.358	0.622	0.241	0.497	0.166	0.393	0.084	0.237
0.729	0.79	0.381	0.598	0.257	0.480	0.178	0.381	0.090	0.231
0.763	0.75	0.402	0.575	0.271	0.464	0.187	0.370	0.095	0.225
0.793	0.71	0.420	0.551	0.284	0.448	0.196	0.359	0.099	0.219
0.819	0.67	0.436	0.528	0.295	0.431	0.204	0.347	0.103	0.214
0.831	0.65	0.443	0.514	0.300	0.422	0.208	0.340	0.105	0.210

$b = 325$ $L = 0.052$ $h = 0.119$		$b = 1{,}500$ $L = 0.0240$ $L = 0.0600$		$b = 6{,}000$ $L = 0.0120$ $h = 0.0305$		$b = 60{,}000$ $L = 0.00378$ $h = 0.00970$		$b = 1{,}000{,}000{,}000$ $L = 0.0000293$ $h = 0.0000752$	
		x	y	x	y	x	y	x	y
0	0.157	0	0.0775	0	0.0394	0	0.0125	0	0.0000971
0.022	0.149	0.0099	0.0735	0.0049	0.0374	0.00156	0.0119	0.0000121	0.0000922
0.029	0.144	0.0132	0.0713	0.0066	0.0363	0.00208	0.0116	0.0000161	0.0000895
0.034	0.140	0.0155	0.0695	0.0077	0.0354	0.00244	0.0113	0.0000189	0.0000873
0.037	0.137	0.0173	0.0680	0.0086	0.0346	0.00272	0.0110	0.0000210	0.0000854
0.041	0.134	0.0188	0.0666	0.0094	0.0339	0.00295	0.0108	0.0000229	0.0000837
0.043	0.131	0.0201	0.0652	0.0100	0.0333	0.00316	0.0106	0.0000244	0.0000821
0.046	0.128	0.0212	0.0639	0.0106	0.0326	0.00334	0.0104	0.0000258	0.0000805
0.048	0.125	0.0222	0.0626	0.0111	0.0320	0.00350	0.0102	0.0000271	0.0000789
0.050	0.122	0.0231	0.0613	0.0115	0.0313	0.00364	0.0100	0.0000282	0.0000772
0.051	0.121	0.0236	0.0605	0.0118	0.0309	0.00371	0.0098	0.0000287	0.0000763

be tremendously large while for thick dams ($L > 1.5h$) the values of b are only slightly larger than 1.0. We did the best we could with the computer we had and chose the following values for b; 1.0000001, 1.0001, 1.001, 1.1, 1.2, 2, 5, 10, 20, 80, 325, 1500, 6000, 60000, 10^9. (These calculations were made on an IBM CPC using floating-point arithmetic, eight significant figures, and an exponent range 10^{-50} to 10^{+50}. It is doubtful that 'double precision' arithmetic could significantly extend our table.) The results of these calculations are presented in Table 1.

The area function—We define a function $A^*(L^*)$ which is the area of the saturated cross section of a dam of length L^* when the upstream liquid height h equals unity. This function will be useful later. These areas were computed by elementary methods and the function is tabulated in Table 2.

Transient-flow solution—In studying a succession of steady states, consider the sketch shown in Figure 5. Liquid is allowed to drain from a semi-infinite porous slab. At some time t during the drainage process the free surface is given by surface 1, the slab for all $x > L$ is still fully saturated. At a later time $t + \Delta t$, surface 2 obtains and the slab is saturated for $x > L + \Delta L$. We know from experiment that this is an accurate picture of the drainage process. The distance L(or $L + \Delta L$) is defined as the effective drainage distance.

TABLE 2 – *Area functions*

b	L^*	A^*
1500	0.30	0.283
325	0.33	0.301
80	0.37	0.341
20	0.44	0.393
10	0.50	0.434
5	0.57	0.487
2	0.73	0.603
1.2	0.93	0.709
1.1	1.02	0.775
1.01	1.38	1.006
1.001	1.67	1.185
1.0001	1.96	1.368
1.0000001	2.46	1.693

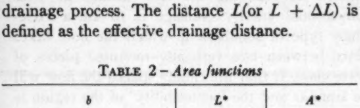

FIG. 5 – Sketch showing succession of steady states

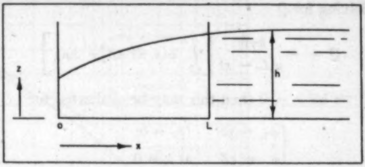

FIG. 6 – Sketch for determining integral expression for flow rate

Now we approximate this transient process by a succession of steady state solutions. The hypothesis is: the rate of flow, Q, at time t is equal to the flow rate through a dam of thickness $L(t)$ of the same permeability with fluid head at the inflow face equal to h. If W is the width of the outflow face and s is the medium porosity then obviously

$$Q \text{ (flow rate)} = Ws\, dA(L)/dt \qquad (16)$$

if A is the area of the saturated area from $0 < x < L$. This may be expressed in terms of the area function $A\ (L^*)$, for if $L^* = L/h$ then $A = A^* \cdot h^2$. We need another expression for Q.

As *Hubbert* [1940] pointed out, the liquid-potential function, $\phi = gZ + (p - p_0)/\rho$, is defined not only within the saturated region but in all space. Of particular interest is its definition in the drained region above the free surface, $\phi = gZ - p_0/\rho$. The flow rate is evidently given by the integral expression (see Fig. 6)

$$Q = -W \int_0^h v_x(x, Z)\, dZ \qquad (17)$$

in which v_x is the x component of the velocity vector ($v_x \equiv 0$ above the free surface).

$$v_x = -\frac{k\gamma}{\mu}\frac{\partial \phi}{\partial x}$$

or equivalently

$$\phi(x, Z) = \frac{u}{k\gamma}\int_x^L v_x(\zeta, Z)\, d\zeta + \phi_L \qquad (18)$$

where ϕ_L is the (constant) potential at the inflow face. Set

$$\begin{aligned} W \int_0^h \phi(x, Z)\, dZ \\ &= W \int_0^h \left\{ \frac{\mu}{k\gamma} \int_x^L v_x(\zeta, Z)\, d\zeta + \phi_L \right\} dZ \\ &= -\frac{\mu}{k\gamma}\, Q(L - x) + Wh\phi_L \end{aligned}$$

Solving for Q

$$Q = -\frac{k\gamma W}{\mu(L - x)}\left[\int_0^h \phi(x, Z)\, dZ - h\phi_L\right]$$

If we let $x = 0$ then this may be evaluated for

$$\begin{cases}\phi_L = gh & (p_0 = 0)\\ \phi = gZ & \text{at } x = 0\end{cases}$$

so that

$$Q = +\frac{h^2 k\gamma W g}{2\mu L} \tag{19}$$

The corresponding equation for drainage rate from a radial system was previously given in an article on water coning [*Meyer* and *Garder*, 1956].

This is the *Dupuit* [1863] equation for gravity drainage rate. It has been derived by valid methods rather than from the incorrect assumptions that he used. (This must certainly be one of few instances where the correct formula was derived from incorrect postulates.) *Muskat* [1946, p. 314] used both this formula and a conformal mapping solution to compute the flow rate through a dam and found good agreement.

TABLE 3 – *Pertinent dimensions*

Experiment	b	h	h'
1	0.0075	19.4	15.6
2	0.0145	18.3	16.3
3	0.0145	19.8	17.8
4	0.0150	19.9	18.0
6	0.0137	20.6	18.5
7	0.01375	19.4	17.3
8	0.0138	19.5	17.4

To determine the transient drainage equation, we combine (16) and (19)

$$Ws\frac{dA}{dL}\frac{dL}{dt} = \frac{h^2 k\gamma W g}{2\mu L}$$

or

$$\int L\frac{dA}{dL}\, dL = \frac{h^2 k\gamma g}{2\mu s}\, t \tag{20}$$

The area function A^* is closely approximated in the region of Table 2 by the linear equation $A^* = 0.636\ L^* + 0.124$, consequently $A = 0.636\ Lh + 0.124\ h^2$. Substituting this into (20), integrating and using the initial condition $L = t = 0$, we obtain

$$L(t) = 1.254\ [\gamma ghkt/(\mu s)]^{\frac{1}{2}} \tag{21}$$

and

$$Q(t) = 0.399\ Wh[\gamma ghks/(\mu t)]^{\frac{1}{2}} \tag{22}$$

Since the derivation of these equations depends on the assumed validity of the approximation by a succession of steady states we would like to compare values computed from them with experimental data.

Experimental drainage studies—An attractive method of studying the free surface in two-dimensional gravity drainage is to use a Hele-Shaw type of simulator in which the flow takes place between two vertically mounted pieces of plate glass. If they are closely spaced the flow will be laminar and the 'permeability' of the region is given by $k = b^2/3$ where b is half the plate spacing [*Rouse*, 1938, sec. 38]. Using this value for the

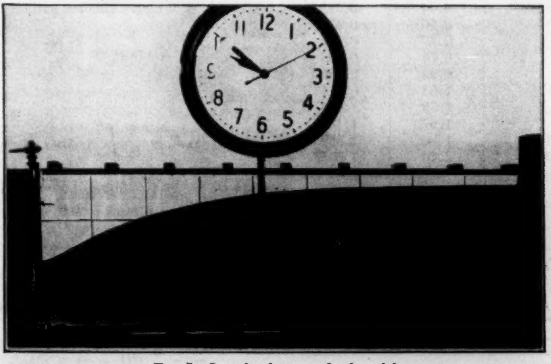

FIG. 7 – Sample photograph of model

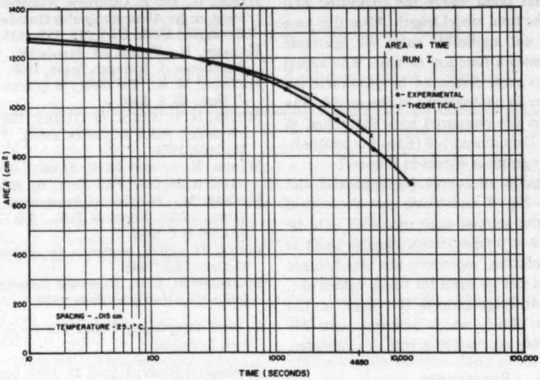

FIG. 8 – Area-time curves for Experiment 1

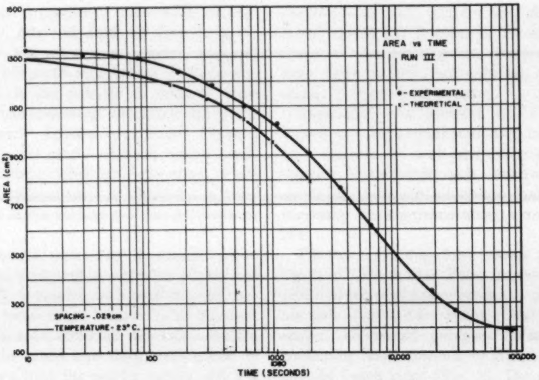

FIG. 9 – Area-time curves for Experiment 3

permeability, (21) and (22) become

$$L(t) = 0.724\, b[\gamma g h t/\mu]^{\frac{1}{3}} \tag{23}$$

$$Q(t) = 0.460\, b^2 h[\gamma g h/\mu t]^{\frac{1}{3}} \tag{24}$$

since $s = 1$, $W = 2b$.

The actual Hele-Shaw apparatus used has been described in a previous paper [*Meyer* and *Searcy*, 1956], for these tests the upstream end of the flow region was sealed and the downstream end was left open. The shape of the free surface was not in good agreement with theory because of capillary effects. Since it is impossible to assign a precise value to L from model photographs we concerned ourselves only with the drainage rate. All studies were made with a fluid (oil) whose specific gravity was 0.8838 and viscosity 1.4857 poise. The pertinent dimensions are given in Table 3. In this table h is the actual fluid height at the start of the experiment, h' includes a capillary correction $h' = h - \sigma/\gamma g h$ where σ is the surface tension of the liquid.

Using b and h' and (23) and (24) the saturated area of the model was computed as a function of time up to that point where the computed $L(t)$ was equal to the total model length. After this time our theory is not applicable since the upstream height h' becomes a function of time. The actual saturated areas were measured by planimetering the shaded area in photographs of the model. The computed areas are compared with the actual in graphs labeled Experiment 1–8 (Exp. 5 is omitted). A sample photograph is shown in Figure 7.

The two families of curves (experimental and computed, see Fig. 8 and 9) do not show good agreement at the start of each run. This is to be expected since $t = 0$ represents a singular point in the analytic solution, moreover the steady-state assumption can not be valid for small values of t. Later in the drainage process the slope of the curves do agree closely which indicates that (24) gives a reasonably accurate flow rate as t increases.

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Rate and Depth of Thaw in Arctic Soils

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Abstract—Measurements at Point Barrow, Alaska, indicate that rate and depth of thaw in Arctic soils are highly related to soil type. Arctic brown soil thawed earlier in the spring, thawed to a greater depth, and froze earlier in the fall than did the adjacent poorly drained areas. During 1956, arctic brown soil thawed to a maximum depth of 40 inches while the depth of thaw in the nearby tundra soil approximated 18 inches. Diurnal near-surface temperature amplitude was greater in the arctic brown than the adjacent poorly drained areas. The willow-lichen-moss complex was the dominant vegetation with the arctic brown soil, while in the tundra soil, it consisted mainly of *Dupontia-Carex-Eriophorum scheuchzeri*. Other vegetation units in relation to soils are given.

A voluminous literature dealing with permafrost research in North America has included important information on depth of thaw in various mineral and organic soil materials under different kinds of plant cover. Geologists, engineers, and botanists [*Black*, 1950; *Cook*, 1955; *Bliss*, 1956; among many others] have endeavored to relate this information to conditions observed in the soil. Until recently, rate and depth of thaw in arctic soils, however, had not been adequately analyzed in relation to soil-profile morphology. Fortunately, in 1955–1956, it was possible to conduct these studies in a small area about one mile south of the Arctic Research Laboratory, Point Barrow, Alaska, where the major regional genetic soils [*Tedrow* and others, 1958] are represented. Field measurements showed marked variations in temperatures and in the thickness of the active layer in these soils.

Arctic brown soil, which most commonly occurs on the higher topographic positions [*Drew* and *Tedrow*, 1957], is present on a well-drained, uplifted marine beach ridge. Because of its exposure to high winds, snow cover on this soil is limited throughout the winter and disappears earlier in the spring than from the nearby tundra and bog soils. Free internal drainage prevents arctic brown soil from accumulating very large quantities of ice. Its surface cover is favorable to absorption of radiant energy, and its low heat capacity permits thawing to begin much earlier and to progress much more rapidly than in adjacent poorly drained tundra and bog soils. Compared with soils on well-drained sites, their initial thaw is considerably delayed. When thawing begins in tundra and bog soils, it progresses at a comparatively slow rate because of their high specific heat resulting from high percentage of ice and lack of free internal drainage, and because of the insulating effect of their organic cover. Variations in plant communities correspond to these differences in soil conditions.

Methods—Observations were made on a sequence of soils located along a north-south transect (Fig. 1) from mid-June until the freeze-back. Depth of snow and of thaw were measured with a steel probe. Soil temperatures were determined in the three-inch depth with ordinary glass immersion thermometers left in place in the soil during the course of the investigation. Preliminary studies were made in 1955, but only the data collected during 1956 are here reported.

Vegetation was sampled by a line-plot-list technique using sample units two inches in diameter centered at four-inch intervals along the transect. Samples from such a small area permitted reasonable estimates of species importance from frequency of occurrence along a segment of the line.

The transect—Permafrost extends to a measured depth of 1030 ft near Point Barrow [*MacCarthy*, 1952]. Much of the land surface is underlain by a network of ground-ice wedges [*Black*, 1950]. High-center, non-sorted polygons [*Washburn*, 1956] containing large amounts of gravel appear along the old beach ridge (Fig. 1). The adjoining low areas of the transect consist primarily of silt and fine sand mantled with tundra and bog soils. Low-center, non-sorted polygons are associated with the tundra soil at the northern end of the transect. Since the polygonal pattern with its associated changes in micro-relief, vegetation, and soil moisture within short distances complicates the measurement of soil conditions, the transect was not extended into the polygonized area. Occasional measurements during the season indicated, however, that the average depth of thaw in the polygonized tundra soils corresponded to data obtained in the tundra soil portion of the transect. The bog soil south of the beach ridge shows little

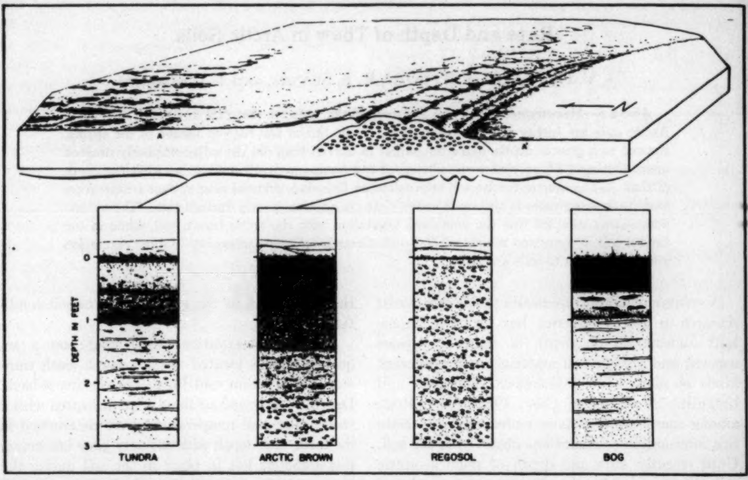

FIG. 1 – Diagram of soil conditions in an area one mile south of the Arctic Research Laboratory at Point Barrow Alaska; vertical scale in the diagram has been exaggerated; the transect shown in Figure 2 extends from A to A′

evidence of polygonization. A small, well-drained gravel terrace near the southern edge of the beach ridge lacks a well-developed profile and is classed as a regosol. The soil profiles (Fig. 1) occurring along the transect are in part idealized. The well-drained arctic brown soil occupies the elevated portion of the transect. The tundra soil is poorly drained, while the bog soil is associated with the poorest drainage in the area. The small terrace adjacent to the beach ridge, termed regosol, consists of well-drained gravel with no perceptible soil development.

The complexes of vegetation present along the transect are representative of the low-lying coastal portion of the Arctic Coastal Plain. Five major vegetation units are recognizable, each correlated with particular physiographic and edaphic factors recognized in the soil mapping units. The polygonized tundra soil north of the transect is characterized by a *Dupontia-Carex-Eriophorum scheuchzeri* complex. In the continuous ankle-deep sward, the arctic grass *Dupontia* characteristically occupies low-center polygon centers and troughs and the sedge *Carex aquatilis* the marginal ridges; the cotton-grass *Eriophorum scheuchzeri* is especially evident along their edges.

Tundra soil on the northern flank of the ridge supports a *Poa-Carex-Arctagrostis* complex which forms a more open sward of lower stature. The better-drained portion of this soil unit, while still grassy in aspect, is characterized by the dwarf round-leaved willow *Salix rotundifolia*, which becomes dominant in the next portion of the transect, and by the composite *Petasites*.

The crest of the ridge characterized by arctic brown soil, exposed and almost snow-free most of the winter, bears a low willow-lichen-moss complex which covers about 80 pct of the surface. At places, the vegetation mat is being removed by the wind, and raw humus and soil are exposed. A tight suppressed growth of lichens (*Cornicularia*, *Thamnolia*, *Sphaerophorus*, *Dactylina*), small clumps of *Luzula confusa*, and scattered plants of arctic bluegrass (*Poa arctica*) characterize this exposed area. On the sheltered south-facing portion of the ridge at the transect station 11 (Fig. 2), such showy-flowered species as *Papaver macounii*, *Pedicularis lanata*, and *Draba fladnizensis* occur, suggestive of the flower slopes elsewhere better expressed, but quite local in the region.

The regosol at the base of the ridge is characterized by discontinuous patches of mat-forming

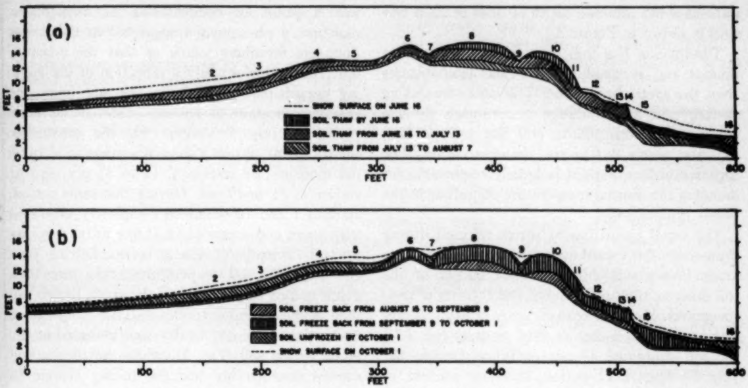

FIG. 2 – Frozen layer positions along the transect (a) shown at three time-intervals from the beginning soil thaw until the time of maximum thaw on August 7; most of the snow cover had disappeared by June 26; numbers along the surface of the profile indicate stations where readings were taken; (b) shown at three intervals from the beginning of freeze-back until October 1; snow began accumulating about September 23 and reached the level ndicated by October 1

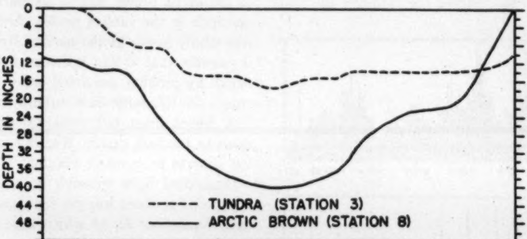

FIG. 3 – Comparison of rates and depths of thaw in arctic brown and tundra soils located on the transect shown in Figures 1 and 2

species, some of which tolerate salt and are found on present-day gravel beaches: *Cochlearia officinalis*, *Saxifraga nivalis*, *S. caespitosa sileneflora*, and *Cerastium beeringianum*.

The marsh vegetation developed on the bog soil at the south end of the transect is dominated by the marsh grasses *Dupontia* and *Arctophila* rooted in peat beneath a spongy carpet of moss. Large *Sphagnum* polsters and such herbs as *Saxifraga hieracifolia*, *S. cernua*, and *Cardamine* occur along the marsh edges.

Discussion—Arctic brown soil, the first to thaw, had thawed to a depth of 11 inches by June 16. The regosol on the small, well-drained gravel terrace (Fig. 2, station 14) was thawed to a depth of three inches by that date. Because of its slightly less effective drainage position and proximity to late-season snow cover, the regosol thaw lagged slightly behind that of the arctic brown. Tundra and bog soils along the transect remained covered with snow and did not begin to thaw until June 26, at which time most of the snow had disappeared. A maximum depth of thaw of 40 inches was found in the arctic brown soil on August 7 (Fig. 2, station 8), while in the tundra soil it was found to be 18 inches on August 11 (Fig. 2, station 3). A comparison of the rate and depth of thaw in these two soils is shown in Figure 3.

Tundra and bog soils pass through a narrower diurnal and seasonal range of soil temperatures than the arctic brown soil. The peaty insulating surface and the blockage of drainage by the frozen layer keep tundra and bog soils at high moisture levels during the thawing period. The higher moisture content is largely responsible for damping the diurnal temperature amplitude in the poorly drained soils.

The small quantities of water released during thaw move downward and escape downslope from arctic brown soil. Approximately 60 pct of the soil mass at the arctic brown site consists of pea-size gravel. Moisture release curves of the < 2 mm fraction indicated that at field capacity (pF 2.7), the soil contained 47 pct moisture. During the July 1 – August 12 period, moisture content in the arctic brown soil (< 2 mm) at station 8 (Fig. 2) varied between 3 and 26 pct. The moisture percentage did not always show a progressive decrease following rainfall; instead, it showed an erratic variation. It is possible that the moisture increase in the soil during the rain-free intervals was a result of condensation of atmospheric moisture, a phenomenon suggested in the Soviet literature for many years, or that the moisture differences were actually a reflection of the varying organic-matter levels in the soil from one sampling location to another. During the same period of July 1 – August 12, the gravel-free tundra soil at station 3 showed a range of 18 to 66 pct moisture; at station 4, 14 to 37 pct; and at station 6, 21 to 79 pct. During this same period, stations 1 and 16 remained completely saturated with water and commonly had free water covering the soil to depths of several inches. During June and early July, soil temperatures at the three-inch depth tended to be higher in the arctic brown soil than in the adjoining tundra soil. Air temperature fluctuations from day to day were reflected in the arctic brown soil (Fig. 4), while the tundra soil showed considerably less day-to-day change in temperature.

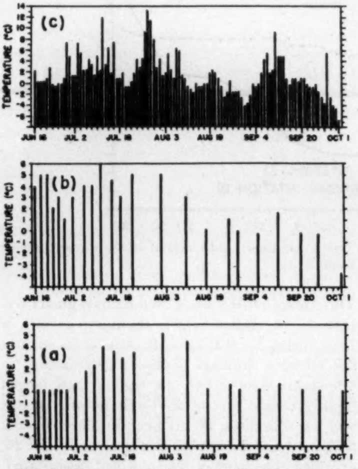

FIG. 4 – Temperature data (a) soil temperatures at the three-inch depth in tundra soil (station 3); (b) soil temperatures at the three-inch depth in arctic brown soil (station 8); (c) daily mean air temperatures from the U. S. Weather Bureau Station at Point Barrow, Alaska (1956)

The top of the frozen layer had begun to move up toward the surface by about August 23. On September 9, it was determined by probing with a steel rod that the frost table had risen 17 inches in the arctic brown soil in comparison with only one inch in the tundra profile. Arctic brown soil was solidly frozen to the surface by October 1 (it is possible that a thin unfrozen zone, difficult to detect by probing, persisted below a thick frozen crust). On this same date, tundra soil had a three-inch frozen crust but remained unfrozen at the three to ten inch depth. Weather conditions were too adverse to continue readings after October 1.

Occasional light snowfall occurred during the summer, but there was no significant snow cover until September 23, at which time it was limited to the tundra and bog soils. A saturated condition, combined with a surface accumulation of organic matter and snow, prevented the tundra soil from freezing as rapidly as did the arctic brown soil. Although the tundra soil thawed less than half as deep as the arctic brown soil, it lagged behind the latter in both thawing and freezing. The maximum depth of thaw in the bog soil was similar to that of the tundra soil. The greater total depth of thaw in the bog soil at the southern end of the transect (Fig. 2), in comparison with that of the wet soils of the northern end, is attributed to the action of light-tracked vehicles that operated daily within a few feet of the southern extremity of the transect.

Reconnaissance observations of the Alaskan Arctic Slope indicate that information on rate and depth of thaw associated with the major genetic soils near Point Barrow can be applied, with minor modifications, to other arctic areas where similar soils and vegetation occur.

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On the Theoretical Derivation of Darcy and Forchheimer Formulas

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Abstract—Darcy's law $\mathbf{q} = K\mathbf{J}$($\mathbf{q}$ = vector of specific discharge; $\mathbf{J} = -\text{grad}\, E$ = hydraulic gradient; E = energy of flow; K = hydraulic conductivity of porous medium) is historically reviewed as well as its numerous extensions. The author starts from the Navier-Stokes hydrodynamic equations of viscous flow, and using statistical methods (space averaging) shows that: The head (or energy) used in Darcy law is different from that used in viscous flow; which recommends large piezometric intakes. The formula $\mathbf{J} = a\mathbf{q} + bq\mathbf{q} + c\partial\mathbf{q}/\partial t$ is obtained (a, b, c = coefficients in isotropic media). Usually the third term may be neglected. At low values of Reynolds numbers, Darcy's law is obtained with $a = 1/K$ in the Kozeny-Carman form. It is found that a = the hydraulic resistivity is more important than K. At larger values of Reynolds number, the Forchheimer formula is obtained, with b depending on the soil texture (grain diameter d) and porosity, not on temperature nor viscosity. The Laplace equation is replaced by a non linear Poisson-type equation with $K = f(J)$. Darcy's law then becomes physically meaningless. A minimum principle is found: Darcy flow is such that the kinetic energy or the dissipation becomes minimum. The application of the Navier-Stokes equations to rocks with seams or cracks gives Darcy's law in its tensorial form.

Introduction—The steady flow of a viscous incompressible and chemically inactive fluid through a saturated homogeneous isotropic and geometrically stable porous medium in the absence of compressible free gases at low Reynolds numbers ($R = qd/\nu$) and at a constant temperature, obeys the Darcy law [*Darcy*, 1856; *Irmay*, 1946, 1947]

$$\mathbf{q} = -K\,\text{grad}\, h = K\mathbf{J} \tag{1}$$

$\mathbf{q}$ = specific discharge (that is, discharge per unit area, dimensions LT^{-1})
γ = unit weight of fluid
ν = kinematic viscosity
d = mean diameter of grains of porous medium
p = pressure
g = acceleration of gravity
Z = elevation above horizontal datum
K = hydraulic conductivity (dimensions LT^{-1}) [*Richards*, 1952] (measures the permeability of the porous medium to the fluid)
h = piezometric head (that is, combined gravity and pressure force potential)

$$h = Z + p/\gamma \tag{2}$$

$$\mathbf{J} = \text{hydraulic gradient} = -\text{grad}\, h \tag{3}$$

Darcy law was extended to non-homogeneous media [*Boussinesq*, 1904a; *Irmay*, 1953], to non-isotropic media [*Irmay*, 1951b; *Schneebeli*, 1953; *Ferrandon*, 1954], to geometrically unstable media [*Florin*, 1948; *Jacob*, 1950], to unsteady flow [*Boussinesq*, 1904b; *Irmay*, 1951a; *Polubarinova-Kochina*, 1952], to compressible fluids [*Muskat*, 1937], to unsaturated media [*Richards*, 1931; *Gardner*, 1946; *Irmay*, 1956a; *Budagovsky*, 1955], and to solutions and adsorptive media [*Edlefsen* and *Anderson*, 1942].

A detailed review of the various theories is given in some textbooks [*Muskat*, 1937, 1949; *Polubarinova-Kochina*, 1951, 1952; *Scheidegger*, 1957].

At larger Reynolds numbers *Forchheimer* [1901] suggested to replace (1) by the non-linear formula which bears his name

$$J = aq + bq^2 \tag{4}$$

See also *Lindquist* [1933]. At low $R(<1)$, the second term may be neglected, and the linear Darcy formula (1) is obtained. Here $a = 1/K$ = hydraulic resistivity of porous medium.

At medium $R(>1)$, the second term is of the same order as the first term. This is the case of a non-linear viscous flow. *Irmay* [1956b] has shown that there is no reason in general to expect a linear solution of the fundamentally non-linear Navier-Stokes equations. The linear Poiseuille solution in straight tubes is an exception caused by vanishing curvature. In flow through porous media the paths are strongly curved.

At larger R (>100) the flow becomes turbulent, as was experimentally shown by the injection of dyes [*Schneebeli*, 1955]. Eq. (4) remains valid, but with different values of a and b. At very large R, $a = 0$ (analogy with rough turbulent flow).

Smreker suggested a different relationship

$$J = Aq^n \; (1 < n < 2) \tag{4a}$$

and *Polubarinova-Kochina* [1952]

$$J = aq + bq^2 + cq^3 \tag{4b}$$

It will be shown later on that the Forchheimer formula is the only one that has a rational basis.

Applying the operation div to the vectorial equation (1)

$$\text{div } \mathbf{q} = -\text{div } (K \text{ grad } h) = 0 \tag{5}$$

In homogeneous media K is constant, and

$$\text{div grad } h = \nabla^2 h = h_{xx} + h_{yy} + h_{zz} = 0 \tag{6}$$

The terms $h_{xx} = \partial^2 h/\partial x^2$, etc. This is the well-known equation of the Laplace potential.

In media of non-uniform K variable in space (5) becomes [*Boussinesq*, 1904a]

$$\text{div } (K \text{ grad } h) = K\nabla^2 h + \text{grad } h \cdot \text{grad } K = 0$$

or

$$\nabla^2 h + \text{grad } h \cdot \text{grad } \ln K = 0 \tag{7}$$

h is a potential of the Poisson type [*Irmay*, 1953]. *Scheidegger* [1957] though, is not sure whether (1) should not be replaced by

$$\mathbf{q} = -\text{grad } (Kh) \tag{1'}$$

which instead of (7) gives

$$\nabla^2 (Kh) = K\nabla^2 h + 2 \text{ grad } h \cdot \text{grad } K + h\nabla^2 K = 0 \tag{7'}$$

Many authors tried to derive Darcy's law by means of various physical and ingenious models and analogies. An excellent review is given in *Scheidegger* [1957]. The models are the capillary-tube analogies [*Smith*, 1932; *Irmay*, 1951a]; the hydraulic-radius theories [*Terzaghi*, 1925; *Kozeny*, 1927; *Irmay*, 1951a]; the drag theories by Emersleben, 1924, 1925 [*Scheidegger*, 1957]; the statistical theories [*Hubbert*, 1940 (or Childs in 1950 and Taub in 1951); *Scheidegger*, 1957]; the thermodynamical theories [*Edlefsen* and *Anderson*, 1943]; the turbulent-flow analogy by Yuhara, 1954 [*Scheidegger*, 1957]; and by direct derivation from the Navier-Stokes equations [*Hall*, 1956; *Hubbert*, 1956].

The above theories have the weak point that they are mostly analogies, the applicability of which has not been proved, or they are based on the introduction of unspecified coefficients, which are somehow ignored in later developments. None of them lead towards Forchheimer's formula.

It will be shown that Darcy's law and even Forchheimer's law may easily be derived from the Navier-Stokes hydrodynamic equations, in the case of viscous flow through a homogeneous isotropic incompressible saturated medium.

Navier-Stokes equations of viscous flow—An incompressible viscous liquid in laminar flow obeys the equation of continuity

$$\text{div } \mathbf{V} = 0 \tag{8}$$

and the dynamic Navier-Stokes equations, summed up vectorially as

$$\mathbf{V}_t - \mathbf{V} \times \text{curl } \mathbf{V} + \text{grad } (V^2/2) = -\text{grad } (gh) - \nu \text{ curl curl } \mathbf{V} \tag{9}$$

where

$\mathbf{V}$ = velocity vector

$\mathbf{V}_t = \partial \mathbf{V}/\partial t$

t = time

$\mathbf{V} \times \text{curl } \mathbf{V}$ = vectorial product

Introducting the energy of flow per unit weight E (dimension L)

$$E = h + V^2/2g = Z + p/\gamma + V^2/2g \tag{10}$$

Eq. (9) becomes

$$\text{grad } (gE) = \mathbf{V} \times \text{curl } \mathbf{V} - \nu \text{ curl curl } \mathbf{V} - \mathbf{V}_t \tag{11}$$

The vectorial operation div gives

$$\text{div grad } (gE) = g\nabla^2 E = \text{div } [\mathbf{V} \times \text{curl } \mathbf{V}] = (\text{curl } \mathbf{V})^2 - \mathbf{V} \cdot \text{curl curl } \mathbf{V} \tag{12}$$

$\mathbf{V} \cdot \text{curl curl } \mathbf{V}$ is the scalar product. Because of (8)

$$\text{div } \mathbf{V}_t = (\text{div } \mathbf{V})_t = 0$$

$$\text{div curl curl } \mathbf{V} = 0$$

Re-written, (12) gives

$$g\nabla^2 E = g\nabla^2(h + V^2/2g) = (\text{curl } \mathbf{V})^2 - (\mathbf{V} \cdot \text{curl curl } \mathbf{V}) \tag{13}$$

At very low Reynolds numbers ($R = Vd/\nu$ with d = characteristic length), that is, when the velocity is very small, the inertia terms, which are of the second order in V, may usually be neglected, when compared to the gravity, pressure, and viscous forces. Approximately

$$\nabla^2 E = 0 \tag{14}$$

assuming $(\text{curl } \mathbf{V})^2$ and $\mathbf{V} \cdot \text{curl curl } \mathbf{V}$ negligible, as being of second order in $\mathbf{V}$. To the same degree of approximation, neglecting $V^2/2g$ we may write

$$\nabla^2 h = 0 \tag{15}$$

This formula holds for any slow viscous flow, it is therefore true for slow laminar flow through a porous medium, whether saturated or not, homogeneous, isotropic, or not.

Eq. (15) is identical with (6), yet the analogy is superficial. In (15), *h* represents the local head *h* at a single point of the viscous fluid flowing in the pores between grains. In (6), *h* represents the space-averaged head $\bar{h}$ in a volume containing a large number of grains and pores, yet small enough when compared with the size of the flow, so as to enable partial derivation. The true viscous and essentially rotational (that is, non-potential) inhomogeneous two-phase flow in the pores between the grains is replaced by a fictitious irrotational (that is, potential) flow through a homogeneous continuous porous medium. This medium is considered as if it consisted of a single phase. This is fiction but becomes true on the average in a sufficiently large volume. This explains why the intake heads of piezometric tubes in soils have to be as large as possible, if consistent data are required.

The discrepancy is even more striking between (15), which is valid also for the flow through the pores of an inhomogeneous medium, and the corresponding Boussinesq formula (7). It is apparent here that *h* has not the same meaning in both cases.

Derivation of the Darcy and Forchheimer formulas—Let us consider one-dimensional flow in the direction x through a homogeneous isotropic medium of average grain diameter *d* and porosity *n*, that is, ratio of voids to total volume of soil. It may easily be shown that this is also the average porosity in a cross section, or the porosity along any direction [*Rose*, 1943].

At any point of the pore space the flow obeys the Navier-Stokes equation (11). In spite of the hypothesis of overall one-dimensional flow throughout the porous medium, we have a three-dimensional viscous flow in the tortuous channels of the medium. In the direction x, (11) gives

$$\begin{aligned} gE_x = \tfrac{1}{2}(v^2 + w^2 - u^2)_x + (uv)_y + \\ (uw)_z - u_t + \nu(u_{xx} + u_{yy} + u_{zz}) \end{aligned} \qquad (16)$$

where x, y, z are the axes of a cartesian system of coordinates; u, v, w the corresponding components of the velocity vector **V**.

Let us now consider a volume, which is sufficiently large, so as to include a great number of grains, and that the conditions of overall homogeneity and isotropy are verified; yet, which is sufficiently small, so that its overall properties do not vary much within it. Let us compute the space average (represented in what follows by an overscore) of (16). The terms v, w are the transversal components. By reasons of homogeneity and isotropy they vanish on the average, as u is the main component. Hence

$$\left.\begin{aligned} &\bar{v} = 0; \quad \overline{w} = 0 \\ &\overline{uv} = 0; \quad \overline{uv_y} = 0; \quad \overline{uw} = 0; \quad \overline{uw_z} = 0 \end{aligned}\right\} \qquad (17)$$

Because of (8)

$$\left.\begin{aligned} u_x &= -v_y - w_z \\ u_{xx} &= -v_{xy} - w_{xz} \\ \overline{u_{xx}} &= -\overline{v_{xy}} - \overline{w_{xz}} = 0 - 0 = 0 \end{aligned}\right\} \qquad (18)$$

The specific discharge q in the direction x is (Fig. 1)

$$\left.\begin{aligned} q &= \bar{u}n \\ \bar{u} &= q/n \end{aligned}\right\} \qquad (19)$$

as n is also the average linear porosity in a direction normal to x.

If L is the average free distance between two grains

$$\left.\begin{aligned} &n = L/(L + d) \text{ or} \\ &L/d = n/(1 - n) \end{aligned}\right\} \qquad (20)$$

Because of the independence of time derivation and spatial integration

$$\bar{u}_t = q_t/n \qquad (21)$$

As the liquid adheres to the walls, there $u = 0$, and u passes through a maximum somewhere in between. Hence the surface $u\ (y, z)$ in a cross section of a pore channel between two grains turns its curvature towards negative x, hence, $u_{yy} < 0$; $u_{zz} < 0$. Averaging, and taking into account (19)

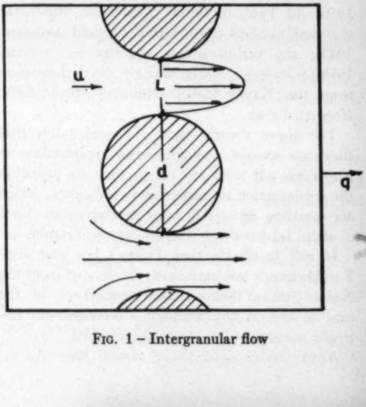

FIG. 1 – Intergranular flow

and (20), we can estimate

$$\bar{u}_{yy} = -\beta_1\bar{u}/L^2 = -\beta_1(1-n)^2/n^3\cdot q/d^2$$

$$\bar{u}_{zz} = -\beta_2\bar{u}/L^2 = -\beta_2(1-n)^2/n^3\cdot q/d^2$$

$$\bar{u}_{yy} + \bar{u}_{zz} = -\beta(1-n)^2/n^3\cdot q/d^2 \tag{22}$$

β_1, β_2, $\beta = \beta_1 + \beta_2$ are numerical shape factors which depend on the shape of the grains and their structure, but not on the porosity or diameter.

In view of (8)

$$\tfrac{1}{2}(u^2)_x = uu_x = -uv_y - uw_z\text{, or }\tfrac{1}{2}\overline{(u^2)}_x = 0 \tag{23}$$

The stream converges when it has to squeeze in between two neighboring grains (Fig. 1). As in the vena contracta $v = 0$, $w = 0$, in the converging zone

$$\overline{(v^2 + w^2)_x} < 0$$

At the large velocities which have to be considered when we study the quadratic terms, there is often separation of flow in the diverging zone, with a much milder degree of divergence than the former degree of convergence. Here $\overline{(v^2 + w^2)_x}$ is either 0 or mildly positive. Hence in both the converging and diverging zones on the average

$$\overline{(v^2 + w^2)_x} < 0$$

In view of (19) and (20) we can estimate

$$\overline{(v^2 + w^2)_x} = -\alpha\bar{u}^2/L = -\alpha(1-n)/n^3\cdot q^2/d \tag{24}$$

where α is a numerical shape factor.

The vector of hydraulic gradient is

$$\mathbf{J} = -\text{grad}\, E \tag{25}$$

and has the components J_1, J_2, J_3 along the axes x, y, z. Introducing (17) to (25) into (16)

$$\bar{J}_1 = -\bar{E}_x = aq + bq^2 + cq_t \tag{26}$$

Similarly

$$J_2 = -\bar{E}_y = 0;\ J_3 = -\bar{E}_z = 0 \tag{27}$$

$$\left.\begin{aligned} a &= \beta\cdot(1-n)^2/n^3\cdot\nu/gd^2 \\ b &= \alpha\cdot(1-n)/n^3\cdot 1/gd \\ c &= 1/ng \end{aligned}\right\} \tag{28}$$

We have thus proved several facts known from experience, and settled a number of controversial points:

(1) At low values of R and steady flow

$$\left.\begin{aligned} \bar{J}_1 &= aq;\ q = K\bar{J}_1 \\ K &= 1/a = gd^2/\beta\nu\cdot n^3/(1-n)^2 \end{aligned}\right\} \tag{29}$$

This is Darcy's empirical formula (1), with Kozeny's expression for K; a is the hydraulic resistivity introduced by the author [*Irmay*, 1953], who has shown its basic importance over the hydraulic conductivity K. Eq. (26) settles this problem.

The whole concept of hydraulic conductivity as defined by

$$K = q/J \tag{30}$$

(we write here J for $\bar{J}_1$ for simplicity's sake) becomes physically meaningless. It may be used only when defined as

$$K = 1/a \tag{31}$$

K as measured by (30) should be abolished from laboratory practice as a universal coefficient and replaced by a.

(2) At higher values of R and steady flow (26) gives

$$J = aq + bq^2 \tag{32}$$

This is Forchheimer's empirical formula (2). This settles the controversy concerning the correct relationship of J to q. The coefficient b depends on the porosity n as $(1-n)/n^3$, and on the average grain diameter d. Hence the effect of larger grains is here more pronounced than in the case of a, which depends on d^2 (larger effect of fines). Coefficient b does not depend on viscosity nor temperature effects, whereas a does so.

(3) The term cq_t caused by unsteady flow is unimportant [*Polubarinova-Kochina*, 1952]. This is independent of the diameter d or temperature. Its effects are felt only initially during a fraction of a second, and may be neglected.

(4) The general case of flow in space may be derived from (26), neglecting only the unimportant cq_t

$$\mathbf{J} = a\mathbf{q} + bq\mathbf{q} = (a + bq)\mathbf{q} \tag{33}$$

with the components

$$J_1 = (a + bq)q_1 \qquad \text{etc.} \tag{33a}$$

From (33)

$$\left.\begin{aligned} J &= (a+bq)q \\ q &= -a/2b + \sqrt{(a/2b)^2 + J/b} \\ \mathbf{q} &= \mathbf{J}/(a+bq) = \\ &\qquad \mathbf{J}/|(a/2) + (a^2/4) + J/b| = \mathbf{J}f(J) \end{aligned}\right\} \tag{34}$$

Applying the operation div to the last equation

$$\text{div}\,\mathbf{q} = \text{div}\,\mathbf{J}f(J) = f(J)\,\text{div}\,\mathbf{J} + \mathbf{J}\cdot\text{grad}\,f(J) = 0$$

$$\text{div}\,\mathbf{J} + \mathbf{J}\cdot\text{grad}\ln f(J) = 0 \tag{35}$$

Eq. (25) gives

$$\nabla^2 E + \text{grad } E \cdot \text{grad } \ln f(|\text{ grad } E\ |) = 0 \qquad (36)$$

This is equivalent formally to (7) when the head h is replaced by the energy E, and the hydraulic conductivity K by

$$F(J) = [a/2 + \sqrt{a^2/4 + J/b}]^{-1} \qquad (37)$$

Eq. (36) is an elliptic partial equation of the Poisson type. This may be solved by a method of *Khristianovich* [1940; *Polubarinova-Kochina*, 1951, 1952].

The principle of minimum—Mathematically (6) is equvalent to the minimum of the integral throughout the volume T of flow [*Courant* and *Hilbert*, 1931]:

$$\int_{(T)} (\text{grad } h)^2 dT = \text{minimum} \qquad (38)$$

or, because of (1)

$$\int_{(T)} q^2 dT = \min \qquad (38a)$$

Darcy flow through a porous medium is such, that the total kinetic energy of flow is minimum; or such, that the dissipation of energy is minimum; as it is proportional to q^2.

This 'minimum principle' seems paradoxical: did not we neglect all second order terms in order to obtain it? And here the flow is conditioned by q^2. The answer is quite simple: second order terms may be neglected, when there are other terms much larger; but one must not neglect such a term, when there is no other. This principle is valid also in Darcy flow in inhomogeneous and non-isotropic media, yet it is not valid, for example, in Forchheimer flow.

Derivation of Darcy's law for media with seams or cracks—The author has applied the Poiseuille solution to the flow in the seams and cracks of cracked rocks, the seams assumed to be straight [*Irmay*, 1955]. In the case of three orthogonal systems of identical and equidistant parallel seams or cracks, Darcy's law is obtained, with the hydraulic conductivity in the Kozeny-Carman form. When the three systems of seams or fractures are geometrically different or inclined, K becomes a symmetrical tensor of rank two, the elements of which are determined by the geometry of the seams. Such a fissured medium is a fair approximation to a non-isotropic porous medium.

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The Measurement of Thermal Conductivity and Diffusivity with Cylindrical Probes

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Abstract—The way in which the temperature of a thermal-conductivity probe (a heated cylinder in an infinite medium) approaches its logarithmic asymptote is discussed. Previous results of Buettner are criticized, in particular his conclusion that it is impossible to measure diffusivity by the use of cylindrical probes. An improved method of determining linear asymptotes for this purpose is described.

Introduction—A recent paper by *Buettner* [1955] discusses the possibility of measuring thermal conductivity and diffusivity by the use of a cylindrical test body or probe. Such methods, which are now assuming considerable importance, are based essentially on the result that if heat is supplied continuously at the rate Q per unit length per unit time for times $t > 0$ along an infinite straight line in an infinite medium initially at zero temperature, the temperature v at time t at distance r from the line is given by

$$\frac{Kv}{Q} = -\frac{1}{4\pi}\,\mathrm{Ei}\left(-\frac{r^2}{4\mathrm{K}t}\right) \tag{1}$$

where K and K are, respectively, the thermal conductivity and diffusivity of the medium, and $-\mathrm{Ei}(-x)$ is the tabulated exponential integral.

For large values of $\mathrm{K}t/r^2$, (1) becomes

$$\frac{Kv}{Q} = \frac{1}{4\pi}\ln\frac{4\mathrm{K}t}{Cr^2} + \frac{r^2}{16\pi\mathrm{K}t}\cdots \tag{2}$$

where $C = 1.7811\ldots$, that is, for large values of $\mathrm{K}t/r^2$, the curve of v against $\ln t$ becomes asymptotically a straight line of slope $Q/4\pi K$ and intercept $\ln(Cr^2/4\mathrm{K})$ on the $\ln t$ axis. Thus any measurement of temperature in a system of this type leads immediately to a determination of K, and, in principle, also of K. Essentially similar results hold for a distribution of parallel line sources as well as for more complicated systems involving composite media and contact resistances.

For measurements in soils, needle probes of small diameter are used. In such cases the linear asymptote is approached in intervals of the order of minutes, and the additional advantage is claimed that in such intervals heat penetrates only into a small portion of the medium so that the conductivity of the material in the immediate neighborhood of the probe is measured. In these cases the quantity r in (2) is a very indefinite one so that there is no possibility of measuring K accurately with a single probe of small diameter.

Blackwell [1954] has studied the problem of making measurements in rock by means of a larger probe inserted into drill holes. In this case the diameter of the probe is several centimeters, and the time taken to reach the logarithmic portion of the curve is a matter of hours. The penetration of heat into the rock is considerable, so that in this case an average conductivity over a region is measured; this is the most useful result for geophysical applications. In this case, the physical system is very nearly the ideal one of a circular cylinder of radius a of perfect conductor of thermal capacity S per unit length to which heat is supplied at the rate Q per unit time per unit length and which is in perfect thermal contact at its surface with an infinite medium of thermal constants K and K. This is the simplest idealization of the probe and has been considered by *Carslaw* and *Jaeger* [1947, p. 284], *Van der Held* and others [1953], *Buettner* [1955], and *Jaeger* [1956]. It is easy to extend it to allow for contact resistance at the surface of the cylinder [*Blackwell*, 1954; *Jaeger*, 1956] or to the case of finite conductivity of the probe [Blackwell, 1954] but at the expense of introducing additional parameters. These more complicated cases will not be discussed below, but they may be treated along the same lines.

Numerical results for a perfectly conducting probe with perfect thermal contact at its surface—For the system described above, the temperature v of the perfect conductor for large values of the parameter $\mathrm{K}t/a^2$ is given by

$$\frac{Kv}{Q} = \frac{1}{4\pi}\left\{\ln\frac{4\mathrm{K}t}{Ca^2} + \frac{a^2}{2\mathrm{K}t} + \frac{(\alpha-2)a^2}{2\alpha\mathrm{K}t}\ln\frac{4\mathrm{K}t}{Ca^2} + \cdots\right\} \tag{3}$$

where $\alpha = 2\pi a^2 K/S\mathrm{K}$.

Thus the slope of the asymptote of the curve of v against $\ln t$ gives K and its intercept gives K/a^2. Provided a is not too small, the only difficulty in

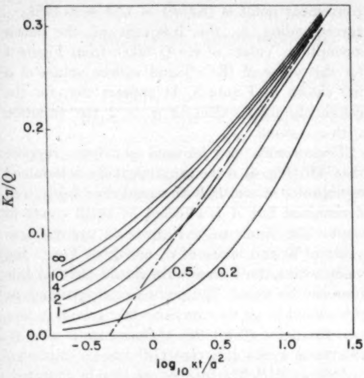

FIG. 1 – The variation of temperature with time for a heated cylinder surrounded by an infinite medium; numbers on the curves are the values of α; all curves have the same asymptote (shown dotted)

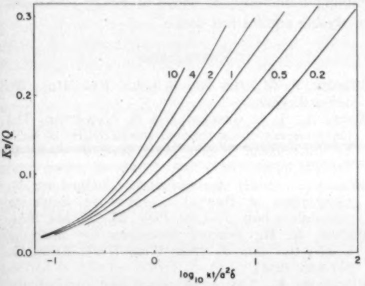

FIG. 2 – The results of Fig. 1 plotted in the manner of *Buettner* [1955]; numbers on the curves are values of $\delta = 2/\alpha$

determining K by this method is that the asymptote is determined at the larger values of $\ln t$ and small errors in its slope may affect the intercept seriously. This point will be discussed later.

Formulas for the temperature at smaller values of the time have been given by the authors referred to above. *Jaeger* [1956] has given some numerical values for such times, but it appears that there are considerable discrepancies between these and Figure 3 of *Buettner* [1955] and the object of the present note is to point out these and their effects on Buettner's conclusions.

Figure 1 shows values of (Kv/Q) plotted against $\log_{10}(\mathrm{K}t/a^2)$ for various values of α. These are mostly taken from *Jaeger* [1956]. The way in which the curves approach the asymptote is seen to be rather complicated, particularly for small values of α, say $\alpha < 1$, when the curves show an inflexion which might easily be mistaken for an asymptote in a short experiment.

In Figure 2 the same quantity Kv/Q is shown plotted against $\log_{10}(\mathrm{K}t/a^2\delta) = \log_{10}(\pi Kt/S)$ for various values of $\delta = 2/\alpha$. This is the plot used by *Buettner* [1955] and this figure is directly com-

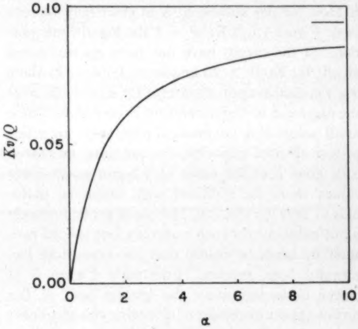

FIG. 3 – Values of Kv/Q as a function of α for $(\mathrm{K}t/a^2) = C/4 = 0.4453$

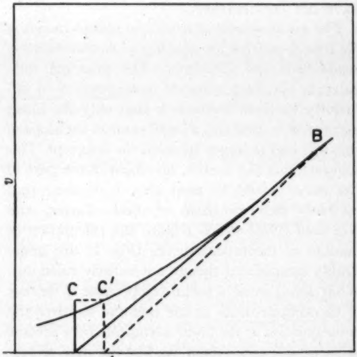

FIG. 4 – Method of using the results of Fig. 3 to improve the determination of an asymptote

parable with his Figure 3. There are very important discrepancies between the two figures, in particular, Buettner's curves for the range $1 < \delta < 10$ lie close together, and from this he concludes that in this range (which includes most practical cases) the rise in temperature of the cylinder depends only on K and very little on δ or the thermal capacity of the soil, so that the thermal capacity of the soil cannot be measured in this way. It appears from Figure 2 that this region is in no way peculiar and these conclusions do not hold.

Buettner further states that in the range $1 < \delta < 10$ the curves are logarithmic for $\mathrm{K}t/a^2 > \delta$. How far this statement is in error may be seen from Figure 1; for $\mathrm{K}t/a^2 = 1$ the logarithmic portions of the curves have not been approximated at all; for $\mathrm{K}t/a^2 > 20$ and $\alpha > 1$, ($\delta < 2$) there is a reasonable approximation; for $\alpha < 1$, ($\delta > 2$) the approach to the asymptote is very slow. These small values of α can occur in practice in materials of low thermal capacity, for example, powdered cork gives α of the order of 0.2 and much lower values would be obtained with expanded materials of very low density. The use of probe methods is not ruled out for such materials, but special care must be taken to ensure that the asymptote has actually been reached. Buettner's Figure 3 is rather misleading since the greater part of the curves appear to consist of diverging straight lines; in fact they all tend to parallel linear asymptotes and most of the field of his Figure 3 corresponds to values of the time in which these asymptotes have not been reached.

The use of theoretical results for smaller values of the time to improve the accuracy of measurements of conductivity and diffusivity—The principal difficulty in obtaining accurate measurements of diffusivity by these methods is that only the linear asymptote is used and a small error in the slope of this will lead to larger errors in the intercept. This suggests that the earlier, non-logarithmic part of the curve should be used also. It is clear that methods such as those of *Beck, Jaeger,* and *Newstead* [1956] which require the calculation of families of theoretical curves (Fig. 1) are undesirably complicated though not entirely ruled out. What seems to be a useful compromise is the use of theoretical values at one point to improve the determination of the linear asymptote by a process of successive approximation. For the case of perfect thermal contact discussed above, the most convenient point is $(\mathrm{K}t/a^2) = C/4 = 0.4453\ldots$ corresponding to the intercept of the linear asymptote. Values of Kv/Q taken from Figure 1 for this value of $(\mathrm{K}t/a^2)$ and various values of α are shown in Figure 3. It appears that for the commonly used values of $\alpha > 2$ the variation with α is small.

These results may be used as follows: suppose that AB (Fig. 4) is the experimentally determined asymptote, of which B is regarded as fairly well determined but A is affected by small errors in slope. The intercept OA gives an approximate value of K and hence of α, and from Fig. 3 the value which the temperature should have at this time can be found. The point C corresponding to this should lie on the experimental curve; if it does not, the point C' for this temperature is used to determine a new intercept OA' and an improved asymptote $A'B$. The process can then be repeated. Clearly, this simple process may be applied to any case in which an accurate determination of the intercept of a linear asymptote is required as in the time-lag methods of *Barrer* [1939] for determining diffusivity, or those of *Brown* [1953] for analysing aquifer test data.

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Velocity of Compressional Waves in Some Indian Rocks*

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Abstract—Velocities of compressional waves have been measured for samples of Indian rocks by direct measurement of times of pulse transmission. These are compared in a number of cases with measurements for the same rocks by the 'wedge' method and by the method of 'critical transmission.' It is concluded that the two latter methods are unsuitable for coarse-grained rocks composed of highly anistropic crystals.

Several studies of wave velocities in Indian rocks have been published [*Prasadarao*, 1947; *Balakrishna*, 1952, 1953; *Krishnamurthi* and *Balakrishna*, 1953; see also *Balakrishna*, 1955]. These have made use either of the 'wedge' method, in which a piezoelectric quartz wedge is used to excite thickness vibrations in a thin plate of sample, [*Bhagavantam* and *Bhimasenachar*, 1944], or the method of 'critical transmission', originated by *Bez-Bardili* [1935] as adapted by Krishnamurthi and Balakrishna. Both of these methods have given reliable results for homogeneous samples (single crystals, glasses) or fine-grained, quasi-isotropic metals; when, as for coarse-grained rocks, the crystal dimensions approach or exceed the sample thickness, the validity of these methods becomes doubtful, and indeed large discrepancies appeared in some cases between measurements for the same rocks by these two methods. It thus seemed desirable to obtain the velocity for some of these rocks by direct measurements of time of transmission of microsecond pulses through samples of a size large enough to afford reasonable average values.

The experimental arrangement has been described by *Tocher* [1957]. A rectangular electrical pulse of duration of about one microsecond, applied across a barium titanate transducer, imparts a compressional pulse to one face of the sample, a prism of rock with ground flat faces. An identical transducer on the opposite face receives the mechanical pulse and supplies an electrical signal to an amplifier and oscilloscope. The trigger pulse is also fed to a Type 326 DuMont time-delay generator; this is used to measure directly the time interval between the start of the electrical pulse and the start of the transmitted pulse. The times are exact to about 0.1 microsecond, of a total travel time of the order of ten microseconds.

TABLE 1.–*Velocities of compressional pulse by time-distance measurement*

Rock	Density	Path length	Travel time	V_p
		mm	micro-sec	km/sec
Granite, gray, Hyderabad	2.66	95.0	15.15	6.27
		70.0	11.4	6.14
		23.0	3.7	6.2
Granite, pink, Hyderabad	2.68	94.4	16.0	5.90
		90.0	15.0	6.00
		63.2	11.2	5.64
Charnokite, Pallavaram	2.75	51.5	8.45	6.1
		49.2	8.0	6.2
		52.3	8.5	6.2
Basalt, Aurangabad	2.91	90.0	15.8	5.70
		64.2	11.25	5.71
		25.9	4.6	5.6
Deccan trap, Igadpuri	2.94	89.4	14.3	6.25
Deccan trap, Ajanta	3.02	64.0	10.0	6.4
Marble, dolomitic, Manditog	2.83	85.2	11.8	7.22
		51.8	7.45	6.95
		40.0	6.05	6.61
Limestone, Shahbad	2.70	54.9	8.4	6.5
		39.8	6.2	6.4
		35.3	5.7	6.2
Limestone, Cuddapah	2.77	95.6	14.3	6.7
Sandstone, Orissa	2.44	71.9	17.4	4.13
		62.8	15.5	4.05
		42.4	10.35	4.10

The results are shown in Table 1, all for room temperature and ordinary pressure. Where three velocities are given for the same rock, these are for three mutually perpendicular directions. These rocks are all nearly isotropic. For comparison with the other methods, the mean values have been entered in Table 2. Samples of a given rock, studied by the different methods, are not identical,

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TABLE 2 – *Determinations of V_p by several methods*

Rock	Pulse transmission (mean)	Wedge	Critical transmission
	km/sec	km/sec	km/sec
Granite, Hyderabad			
gray	6.20	6.17, 6.40	6.40
pink	5.85	6.05	7.16
Charnokite, Pallavaram	6.2	6.24	7.58
Deccan trap, Igadpuri	6.25	6.36	6.70
Ajanta	6.4	6.48	6.58
Marble, Manditog	6.93	6.83, 7.57	6.83, 7.33
Limestone, Shahbad	6.4	6.21	6.24
Cuddapah	6.7	6.60	6.40
Sandstone, Orissa	4.09	4.20	4.06

and a sampling error, increasing as the size of sample is reduced, is to be expected. The samples studied by the wedge method and by critical transmission are only a few millimeters thick, to be compared with path-lengths of the order of 50 mm for the transmission-time measurements. In addition, the simple theory becomes seriously inadequate for the wedge and critical transmission methods when the sample consists of a small number of large crystals, having different orientations or different properties.

The comparative values of Table 2 are in general accord with these expectations. Fair agreement by all methods is shown for several of the rocks of finest grain: the sandstone, limestone, and trap. The wedge method on the whole shows better agreement with the direct time measurements than does the critical transmission method, which furnishes widely aberrant values for the coarse-grained granites, charnokite, and marble. These methods, wedge and critical transmission, are especially valuable for small samples of homogeneous material; they are evidently unsuitable for coarse-grained rocks.

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K-A and Rb-Sr Methods and Age of Precambrian of USSR

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Abstract—The procedure of mica age determination by the K-A method is described. The age data obtained by the K-A and Rb-Sr methods for Precambrian of the USSR together with their estimation are given. The data obtained are compared with the stratigraphy.

Our work was carried out by the K-A method since 1951 and by the Rb-Sr method since 1956. It is found that micas give the most reliable results. The evolution of argon from micas is connected with the great value of the activation energy, which may be compared with the energy of the bonds of the most stable chemical compounds. The activation energy found for the evolution of argon from muscovite, biotite and phlogopite is [illegible]5,000, 57,000, and 65,000 cal per gram atom argon respectively [*Gerling* and *Morosova*, 1957].

The evolution of argon is accomplished by the heating of micas for five hours at the temperature of 1200°C. The argon evolved is measured on a MacLeod manometer after the absorption of the chemically active gases and the separation from helium. The content of the air argon in samples is measured on the mass spectrometer with the aid of the isotope A^{36}. It was found that together with the evolution of argon from fluorine containing micas the formation of a molecular compound of argon takes place and the part of argon or even its whole amount is absorbed in the trap with liquid air. It was set so that by the heating of fluorine containing micas the mixture of silanes with the predominance of light SiH_4 evolved from these micas. The absorption of argon by liquid air takes place only in the presence of water vapor and silanes. Silane with water forms a molecular compound of the type SiH_46H_2O with which $A6H_2O$ crystallizes isomorphically. If the gases from micas are passed over the copper oxide at 600°C the silanes will oxidize and the formation of this compound in the trap with liquid air will not occur [*Koltzova*, in press].

The determination of K is made by the chloroplatinate and perchlorate methods. Rb is determined by application of radioactive tracers [*Jaschenko* and others, in press] or by the method of isotopic dilution. When calculating the age, the value of the electron capture disintegration constant of 6.02×10^{-11} year $^{-1}$ is used. This constant was calculated by us by means of the argon determination in micas the ages of which were obtained by the Pb method. For the beta emission disintegration constant of K^{40} the value of 4.9×10^{-10} is used.

Since 1951 more than 300 determinations of age of micas from different regions of the Precambrian of the USSR were made (M. L. Jashchenko, G. M. Ermolin, L. K. Levsky, L. I. Afanasieva, G. V. Ovchinnikova, T. V. Koltsova, I. M. Morozova, I. I. Matveeva, and V. D. Bugrova). Some of the data obtained were published by *Gerling* [1956] and *Gerling* and other [1955, 1957].

Some age determinations of rocks obtained by the K-A method on micas collected by geologists D. A. Velikoslavinskii, K. O. Kratz, V. A. Maslenikov, S. V. Obrutchev, N. G. Sudovikov, K. A. Shurkin, and others are shown in Table 1.

The age of the Precambrian of different districts of the USSR ranges from 2880×10^6 to 500×10^6 years. The oldest rocks are found on the Kola Peninsula. For some gneisses and granites age values of 2600×10^6 years were obtained. One of the age values is even 2880×10^6 years. It should be noted that for the Mesozoic and Paleozoic rocks there was no great divergence between the K-A method and stratigraphy in any case. Usually a good agreement in the data of both methods was obtained, the divergence with the geological data being insignificant.

However, the figures for the Precambrian given in Table 1 show the great difference between the age of some rocks by the K-A method and the geological data. Sometimes this difference reaches 10^9 years. We believe that this disagreement in the age of Precambrian is not connected with the incorrectness of the K-A method as is shown by the numerous age determinations of rocks from the Paleozoic era, and younger, and also by some comparative data between the K-A, Rb and Rb-Sr methods for the Precambrian of Ukraine and Siberia.

The samples in which the difference with the geological data was very great were examined. The age of the upper Proterozoic rapakivi granites of the

TABLE 1 – *Data on age determinations*

No.	Mineral	Locality	Geological age	Age in 10^6 years
1	Biotite from granite	Kola Peninsula, region of the m. Shulwave	Lower Archean	2880
2	Biotite from gneiss	Kola Peninsula, River Voronya	Lower Archean	2650
3	Biotite from granite with microcline	Kola Peninsula, River Voronya, Rapids Dyavolov	Lower Archean	2600
4	Biotite from gneiss of Polmas suite	Kola Peninsula, region of m. Shulwave	Lower Archean	2170
5	Biotite from gneiss of Polmas suite	Kola Peninsula, Kontozero	Lower Archean	2300
6	Biotite from plagioclase-microcline granite	Kola Peninsula, region of Porkozero	Lower Archean	2230
7	Mica from pegmatite	Kola Peninsula, m. Okhmilk, vein N 3	Lower Archean	2250
8	Mica from plagiogranite	Ukraine, Krevoy Rog	Lower Archean	1990
9	Mica from pegmatite of plagioclase granites	Ukraine, region of the village of Petrovo	Lower Archean	1980
10	Mica from gneisses	Ukraine, region of the village of Petrovo	Lower Archean	1980
11	Muscovite from pegmatite	Ukraine, Gitomir District, village Glubotchek	Upper Archean	1840
12	Muscovite from pegmatite	Ukraine, town of Korostichev	Upper Archean	1810
13	Mica from schists	Ukraine, village Appovka, Krivorogye	Lower Proterozoic	1820
14	Mica from the red granite intersecting the schists of the Krivorogye formation	Krivorogye, Balka Gladovoy, Ukraine	Lower Proterozoic	1860
15	Mica from gneiss	Karelia, Mine Karelsky, Kopatvaraka	Upper Archean	1850
16	Muscovite from pegmatite	Karelia, Tchkalov mine, vein of the 8th of March	Upper Archean	1740
17	Mica from the fine grained granite	Karelia, Archipelago Kandalakshsky Island Demenikha	Upper Archean	1890
18	Biotite from the gneiss of Anabarsky shield	Siberia, upper part of River Kenady	Archean	1900
19	Phlogopite	Siberia, Aldansky Shield, mine Taegenoy	Archean	1790
20	Phlogopite from metasomatic vein	Siberia, Aldansky Shield, Kurum-Khanku	Archean	1840
21	Biotite from gneiss intersected by metasomatic vein	Siberia, Aldansky Shield, River Tchuga	Archean	1870
22	Muscovite from pegmatite	Siberia, Cape Tiganoss	Archean	1700
23	Biotite from the schist of the Ladoga formation	Karelia, North Preladogye, western beach of the Cape Iminiemy	Lower Proterozoic	1640
24	Muscovite from the granite injected in the schists of Ladoga	Karelia, North Ladoga	Lower Proterozoic	1620
25	Muscovite from the schist	Karelia Lake Pukhya-Jarvy	Lower Proterozoic	1660
26	Biotite from quartz-biotite-amphibolic schist	Karelia, Parandovo	Lower Proterozoic	1650
27	Biotite from the schist	Karelia, village Guimaly	Lower Proterozoic	1740
28	Mica from the Korostene massive rapakivi granite	Ukraine, Korostensky massive	Upper Proterozoic	1660
29	Micas from the Viborg massive rapakivi	Baltic Shield, Viborg	Upper Proterozoic	1520
30	Mica from syenite of the Mariupole Complex	Ukraine, village Oktyabrskoe	Upper Proterozoic	1470
31	Biotite from granite	Kola Peninsula, Region Kontozero	Lower Proterozoic	1110
32	Glauconite	China, Sinian formation	Upper Proterozoic	650
33	Muscovite from pegmatite	Siberia, Region Birussinsky, mine Neroy II	Upper Proterozoic	492
34	Phlogopite from vein	Siberia, Sludyanka	Archean	462
35	Muscovite from pegmatite	Siberia, Mamsky region, mine Severny	Lower Proterozoic	337

Korosten Complex of the Ukraine, was equal by the lead method on the zircons to 1700 × 10^6–1750 × 10^6 years and by the K-A method to 1660 × 10^6 years (No. 28 in Table 1). These values agree between themselves quite well.

The K-A age of the Archean phlogopite from Sludyanka, Siberia, (No. 34) of 462 × 10^6 years is quite near to the Pb^{207}/Pb^{206} age of the zircon (450 × 10^6 yr) and to the Pb^{208}/Th^{232} age of the monazite (500 × 10^6 yr). (The Pb ages were determined in the V. I. Vernadsky Institute of the Analytical Chemistry and Geochemistry of the Academy of Sciences of the USSR [*Vinogradov* and others, 1957; *Girova* and others, 1957].

Micas of the Lower Proterozoic age of the Mamsky region of Siberia are dated according to the K-A method as 337 ×10^6 years and according to the Rb-Sr method as 420 × 10^6 years.

Mica from the Kola Peninsula, from the formation related to the Lower Proterozoic is dated according to the K-A method as 2200 × 10^6 years and according to the Rb-Sr method its age ranges from 2200 × 10^6 to 2600 × 10^6 years [*Jashchenko* and others, in preparation].

The above-mentioned examples show that the age data of mica from the rapakivi granite and of the micas from the pegmatite Mama and Birussa region in Siberia are not connected with the excess of argon or with its loss. The other problems of the K-A method, in the case where the age of the pegmatite mica proved to be 1000 million years older than the age of the mica from the gneiss intersected by the pegmatite, are now being examined. Polkanov believes that further research by the K-A method may put forward the question of the Precambrian of the Baltic and Ukrainian shields belonging to different periods of the Archean, with an age of over 1500 million years, and of the 'archeische Scheitel der Asia' (E. Suess), Siberia, to the Proterozoic-Paleozoic era, with the age of under 500 million years respectively.

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An Optical Method for the Measurement of Surface Waves in the Laboratory*

ALAN J. FALLER

Abstract—The heights of surface waves in a laboratory experiment may be observed by variations in the absorption of light as it passes vertically through the fluid. With uniform illumination through the glass bottom of a tank the optical path length through a black dye solution may be recorded photographically from above the tank and the heights of surface waves may be measured from the film density. A linear relation between film density and wave height is possible if the 'straight-line' region of a film blackening curve is used and if the dye has a sufficiently constant absorption coefficient in the band of significant wave lengths. Optimum results are obtained by using as strong a concentration of dye as the intensity of illumination permits and by selecting a film with maximum contrast. In a simple experiment it was found possible to measure variations of the height of the free surface of the fluid to an accuracy approaching one per cent of the total depth, but significantly greater precision may be possible by using more elaborate apparatus.

Introduction—In a large variety of laboratory experiments involving gravity waves both at the free surface of a fluid and at the interface between two fluids it is desirable to have precise measurements of the wave structure; for example the waves produced by or which interact with towed ship models, waves created by the action of wind stress, or internal gravity waves which may exist in stratified models of oceans, rivers, or lakes.

This particular study was motivated by a desire to measure the height of the interface of two fluids in a two-layer atmospheric model developed by *Fultz* [1952] at the University of Chicago. In this model it is possible to represent the polar dome of cold air and the wave cyclones that occur along frontal surfaces in the atmosphere. The precise details of the generation of these waves at the interface of the two fluids are adequately described in the above reference and are not significant to the particular technique developed here.

The essence of the optical method by which these waves were to be measured was to provide a glass bottom in the circular tank, and to illuminate the fluids uniformly from below, so as to photograph the variations of optical density from above. In this technique the resultant film density could be calibrated as a function of the vertical thickness of the dyed fluid (either the lower or upper fluid), and the detailed shape of the interface of the two fluids could be determined from analysis of the film density pattern with a microdensitometer.

In an attempt to reproduce this model and to measure the depth of the interface, optical difficulties were encountered which rendered the method impractical for this particular experiment. Because of the necessarily small difference in the specific gravities of the two fluids (adjusted to a difference of 0.005), a colloidal suspension of water droplets was produced in the mixture of chlorobenzene and toluene (water being the less dense fluid and the mixture the more dense). In addition a detergent was required to reduce the interfacial tension between the two fluids and the problem was complicated by a precipitate from the detergent. The optical technique seemed to have more general applicability, however, and was developed further for the measurement of surface waves on water.

THEORY

The relation of film density to depth of liquid—In the following discussion it will be assumed that there is sufficient illumination to work in the 'straight-line' portion of a film response curve, that is, where the film density D is linearly related to the logarithm of exposure [see for example *Neblette*, 1938, or other texts on photographic theory]

$$D = C_0 \log (\text{exposure}) + C_1$$

In terms of film and illumination characteristics this statement becomes

$$D = \gamma \log \int C_2 P_{0\lambda} S_\lambda e^{-k_\lambda^{\,s}} t \, d\lambda + C_1 \tag{1}$$

where γ is the slope of the film response curve; C_1 includes the base density of the film and the inertia of the emulsion; S_λ is the sensitivity of the film to radiation of wave length λ; $P_{0\lambda}$ is the relative illuminating power per unit wave length incident on the bottom of the wave tank; C_2 accounts for losses by reflection at the interfaces of air, glass, and water; k_λ is the absorption coefficient per unit wave length; t is the duration of the exposure; and z is the geometric path length in the dyed fluid. If k_λ equals a constant $\bar{k}$, (1) may be written in the form

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* Contribution No. 945 from the Woods Hole Oceanographic Institution.

$$D = -\gamma \bar{k} z \log e + \gamma \log t + \gamma \log \cdot \int C_2 P_{0\lambda} S_\lambda \, d\lambda + C_1 \quad (2)$$

For constant values of $P_{0\lambda}$, S_λ, C_2, t, and C_1 (that is, constant experimental conditions) we deduce the following linear relation between D and z

$$D = -(\gamma \log e) \bar{k} z + C \quad (3)$$

which may be differentiated to obtain

$$\frac{\partial D}{\partial z} = -\gamma (\log e) \, \bar{k} \quad (4)$$

From the above it is clear that the maximum sensitivity of density change to depth change exists for maximum values of γ and $\bar{k}$ and that it is desirable to use as high a concentration of dye as possible and a film which may be developed to high contrast.

It is important to note that appreciable changes in the value of $\bar{k}$ may require unreasonably large changes in the intensity of illumination required to produce the same film illumination P. Suppose the dye concentration is doubled and x is the factor by which P_0 must be increased to produce the same value of P. Then

$$P = P_0 e^{-\bar{k}z} = (xP_0) e^{-2\bar{k}z}$$

$$x = e^{+\bar{k}z} = P_0/P$$

In a particular example described below P_0/P = 48; therefore the illumination would have to be increased by this factor to double the sensitivity by increasing the dye concentration. Greater variations may be had through variation of the film contrast.

Errors caused by refraction and internal reflection—Because a ray path through the dye solution passes obliquely and with varying angles through the air-fluid interface there are inherent errors due to refraction and internal reflection. To simplify the discussion it will be assumed that the camera is sufficiently far from the water surface that the effect of the viewing angle of the camera may be neglected.

A simple consideration of the refraction due to the slope of waves using Snell's Law shows that for a wave slope of angle i the percentage error in the total depth of the fluid is as given in Table 1.

TABLE 1 – *Refraction errors at an air-water interface*

i	error
°	pct
10	0.1
20	0.3
30	1.0
40	1.9
50	3.4

The significance of these errors depends upon the accuracy required and the amplitude of the waves with respect to the total depth of fluid, but it is apparent that for many problems this error may be small enough to be neglected. If it should be necessary to apply a correction for refraction, the approximate wave slopes could first be determined and the correction applied as a second order effect. However it would also be necessary to consider the viewing angle of the camera if this angle deviated appreciably from the normal.

A computation of the reduction in light intensity caused by the variation of internal reflection with angle of incidence from Fresnel's formulas showed that this effect is generally small compared to the refraction effect and may be neglected in all cases except for extremely steep waves. In a two-layer model, errors caused by refraction and internal reflection would be negligible because large incident angles would occur only at the interface of the two fluids where the difference between indices of refraction would be much smaller than at an air-water boundary.

An alternate method of conducting experiments would be to illuminate from above and to photograph from below so that the path length through the fluid would not depend upon refraction at the disturbed air-fluid interface. Most experimental arrangements, however, would not permit the use of a camera at a sufficient distance beneath the apparatus.

Errors caused by inaccurate exposure time and uneven illumination—From (2) it is apparent that a change in the duration of exposure t would not affect $\partial D/\partial z$ and would only add a constant density correction to the entire film. Such an error would be easily recognized in the average density, and the correction could be determined by assuming that the average depth of water was the same over the observed area with and without waves. Of course it is necessary to use a sufficiently rapid exposure that the waves to be observed do not move a significant fraction of their wave length in the exposure interval. For the example discussed below the speed of gravity waves would have been approximately 50 cm/sec and in the exposure interval of 1/200 sec the waves would have moved only 0.25 cm compared to an observed wave length of 13 cm.

Errors produced by uneven illumination from below may be determined by a 'null' experiment, that is, no waves. It is again evident from (2) that $\partial D/\partial z$ is independent of $P_{0\lambda}$ and the additive correction to D is a function of position alone. In the experimental example below this correction was applied by graphical subtraction of the 'null' contours from the wave contours.

Note that these simple corrections are possible only when the exposures remain in the 'straight-line' portion of the film-response curve.

A SIMPLE EXPERIMENT

An apparatus was constructed (Fig. 1) to test the utility of the method. A symmetrical wave pattern was generated in a circular tank (with a plate glass bottom) by tapping one side of the tank sharply so as to generate waves of equal amplitude but opposite phase on opposite sides of the tank. Uniform diffuse illumination was approximated by five equally-spaced photofloods shining on a white background. Although the illumination appeared uniform to the eye, the film, developed to extreme contrast and analyzed with a microdensitometer, showed marked variations in density from 0.82 at the center to 0.50 near the rim with some minor irregularities. The camera, a Ciroflex Model D, was mounted 38 inches above the water surface to obtain the maximum image size.

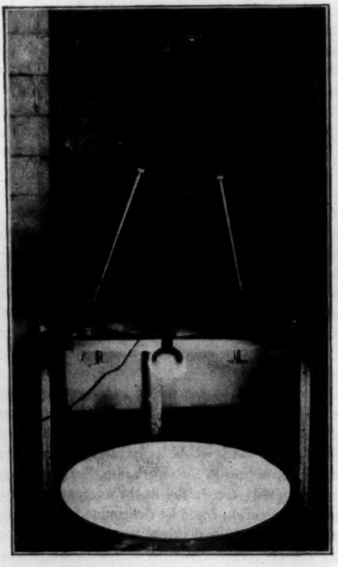

FIG. 1 – The experimental apparatus showing the circular tank with a glass bottom, illuminated from below and photographed from above

A means for calibrating the relationship of depth to density of the film was provided by the three leveling screws which supported the platform, tank, and tripod. By raising one of the supporting screws a linear variation of depth of fluid could be produced over any desired range from one side of the tank to the other.

Several black dyes were tested for spectral dependence of the absorption coefficient, and it was shown that for the conditions of the experiment (spectral film sensitivity, dye concentration and illumination spectra) water-soluble black nigrosine was sufficiently close to a uniformly black dye that the entire visible spectrum could be used with the assumption k_λ was equal to a constant.

The conditions of the experiment were as follows:

Dye concentration, water-soluble black nigrosine, 0.043 g/L.
Depth of solution, 1 inch
Diameter of tank, 18 inches
Relative illumination as measured by a GE DW68 exposure meter: before adding dye, 620; after adding dye, 13
Optical density of solution, 1.68; $\bar{k} = 4.03$ in^{-1}
Verichrome orthochromatic film developed 15 min at 23°C in D-19 developer
Duration of exposure, 1/200 sec
Lens aperture, f/5.6

The microdensitometer used for the analysis consisted of a microscope with a constant light source and a stop of 40 μ diameter. Light transmitted through this area of the film was received by a photocell and the output was displayed on the meter of an Ansco Color densitometer. Because of film granularity the meter fluctuated erratically by ± 0.05 as the film was transported continously across the optical system. For the wave analysis 1400 observations on a grid interval of 1 mm (image diameter 42 mm) were obtained.

Three photographs of the 'null' experiment were analyzed to obtain the illumination correction and to estimate variations of the shutter speed. The average film density was 0.70 and the difference between the lightest and the darkest points was 0.09. Measurements with the tank tilted from $z = 0.75$ on one side to $z = 1.25$ at the other gave a value of $\partial D/\partial z = -2.80$ in^{-1}. From (2) the approximate shutter speed variation may be determined

$$\frac{\partial D}{\partial t} = \frac{\gamma \log e}{t} = -\frac{1}{\bar{k}t}\frac{\partial D}{\partial z}$$

or for small finite differences

$$\Delta D = -(\Delta t/\bar{k}t)\Delta D/\Delta z$$

For the range of densities of 0.09 for the three trials the range of shutter speeds was 13.5 pct. A value of $\gamma = 1.6$ may also be obtained from the above value for $\partial D/\partial z$ uzing $\bar{k} = 4.03$ in^{-1} as determined approximately from exposure meter measurements. Much higher values of γ and greater sensitivity could be obtained by the selection of a special high contrast film.

Figure 2 is an analyzed wave pattern superimposed on a print of the wave photograph, the waves having been generated by tapping one side of the tank sharply. Contour heights are in terms of inches with a maximum variation from the average of ±0.1 in. The contour intervals are not quite constant because the contours were analyzed

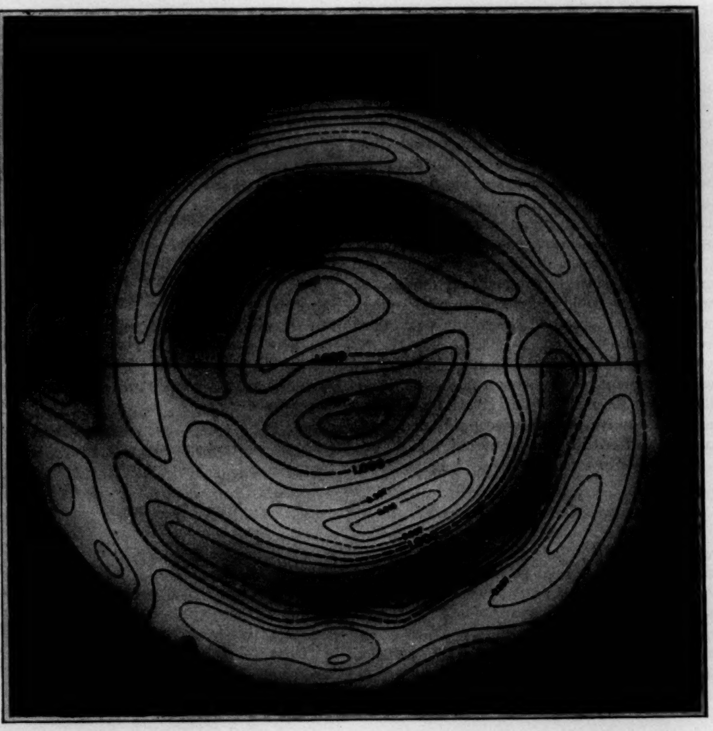

FIG. 2 – A microdensitometer contour analysis of waves superimposed upon the wave photograph; the contour interval is approximately 0.05 inch

on the basis of density and because the curve of the relationship of depth to density was not quite linear in this range of densities (approaching the toe of the film response curve).

The effect of the uneven illumination has been corrected in the contours by graphical subtraction of the 'null' density pattern from the pattern with waves. This effect is apparent in the print densities, however, which become darker (for the same contour height) nearer the rim. (Some error also is introduced in the superposition of the two patterns.) Small-scale irregularities are attributed to granularity of the film which led to erratic individual density values some of which have been smoothed out in the analysis. In defense of the method it should be added that no reference was made to the print of the wave pattern until the countour analysis had been completed.

CONCLUSIONS AND RECOMMENDATIONS

This optical method is suitable for obtaining the three-dimensional structure of a water surface, and rapid sequence photography can extend the technique to time variations. A complete record is obtained which may be analyzed selectively at a later date. Analysis of a large number of films could be accomplished by an automatic scanning device which could smooth fine-scale irregularities of the film and could apply a predetermined illumination correction automatically. Such a scanning system could be designed to produce the wave profile or spectrum along any particular direction.

Another technique for the analysis of the contours of constant density from a film is that developed by *O'Brien* and *Stewart* [1938]. By making successive positive and negative prints on Eastman Kodak Kodalith film an overall γ of 40 or more was obtained in which case a line of constant density appeared as a sharp boundary between black and white areas on the final negative. Different contours were selected by varying the exposure on the final positive Kodalith transparency. The principal difficulty in application to wave analysis would be the production of sufficiently uniform illumination that variations from this source would not contribute to significant density variations.

It is the author's opinion that by selecting a more suitable film, by producing more uniform illumination, and by smoothing of film irregularities an accuracy of better than one per cent of the total depth could readily be obtained, and that greater precision is possible under ideal conditions. Regardless of the accuracy of the method, a wave pattern photograph is obtained that is readily interpreted qualitatively.

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Progress Report, Seismological Laboratory of the California Institute of Technology, 1957*

HUGO BENIOFF, BENO GUTENBERG, FRANK PRESS, AND C. F. RICHTER

GENERAL INFORMATION

On July 1, 1957 Beno Gutenberg retired as Director of the Seismological Laboratory and was succeeded by Frank Press. Beno Gutenberg remains a member of the staff. On February 5, 1958, Harry O. Wood, who founded the Seismological Laboratory, passed away after a long illness.

The long-standing condition of overcrowding at the Seismological Laboratory was corrected by the acquisition of an adjacent property. The new quarters, known as the Donnelley Laboratory, house offices for staff, visitors, and students as well as a library, map room, seismogram analysis room, and ultrasonic seismic model laboratory. An important feature of the Donnelley Laboratory is a tunnel 150 ft long, located in granite at a depth of 60 ft beneath the building. A linear strain seismograph and ultra long-period pendulums will be installed in the tunnel. The old quarters are being extensively remodeled and will be known as the Kresge Laboratory, housing the main seismograph vaults and recording rooms, experimental piers, electronics laboratory, machine shop, storage and stock rooms, photographic dark room, and offices for technicians.

STATION DEVELOPMENT

New station—San Nicolas Island, California (33° 14.9′N, 119° 31.4′W, h = 275 m) established July 24, with the support of the Office of Naval Research. Equipment: Benioff Z-component reluctance pendulum ($T_0 = 1.0$ sec.) with $T_g =$ 0.25 sec and 70 sec and one E-W torsion seismograph ($T_0 = 0.8$ sec).

Pasadena—Press-Ewing seismographs ($T_0 =$ 30 sec, $T_g = 90$ sec) discontinued operation at old seismological laboratory (now Kresge Laboratory) and installed with three components at the new Donnelley Laboratory near the end of September. Benioff reluctance Z component ($T_0 = 3$ sec, $T_g =$ 100, $Z_0 = 125000$ ohms; $C = 400$ mfd) transferred to Donnelley Laboratory.

Big Bear—Station discontinued September 20, 1957.

Hayfield—New housing occupied May 1, 1957. Benioff reluctance Z component seismograph ($T_0 = 1.0$ sec, $T_{g1} = 0.25$ sec). Second galvanometer ($T_{g2} = 70$ sec) added July 16, 1957.

Isabella—On September 10, 1957, torsion seismograph discontinued; ink-writing recorder for tidal strains and long period seismic waves installed on quartz extensometer; galvanometer with 600-sec period and displacement transducer installed on quartz extensometer for recording of long period seismic waves.

Palomar—Long-period ($T_g = 70$ sec) galvanometer added to Benioff reluctance Z-component seismograph December 10, 1957.

Dalton—Ink-writing recorder installed on quartz extensometer for recording tidal strains and long period seismic waves.

Additional instruments—Geomagnetic recording variometers ($T_g = 1.2$ sec) were installed as follows with the support of the Office of Ordnance Research, U. S. Army: Palomar, single photographic N-S component; Isabella, three-component photographic (N-S, E-W, and Z); Pasadena, single-component N-S heated stylus visible writing ($T_g = 0.5$ sec); Resolute Bay, Canada, single N-S component photographic, with the cooperation of the Department of Mines and Technical Surveys of Canada, and John H. Hodgson and P. L. Willmore.

INSTRUMENT DEVELOPMENT

Long-spread portable seismograph system (*Frank Press*)—In crustal exploration using reflected and refracted waves from explosive sources, it is important to have significantly larger distances between detectors than is customary. A system has been designed and used capable of providing records on a single oscillogram from six detectors spaced one km apart. This provides the necessary phase lag for identifying reflections, second arrival refractions, and determining apparent velocities of these events.

Strain recorder for long period waves (*Hugo Benioff*)—A galvanometer of 600-sec period is connected through a large capacitor to the carrier-current capacity-bridge transducer of the Isabella extensometer. The transducer output voltage is proportional to ground-particle velocity. The time constant of the network consisting of the coupling capacity and series resistances is four seconds. Hence, for the long-period waves of interest ($T >$ 30 sec) the voltage input to the galvanometer is proportional to the ground-particle acceleration and the resulting response of the galvanometer is nearly proportional to ground displacement for waves from about 30- to 600-sec period. These characteristics are particularly useful for mantle Rayleigh waves and G waves.

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*Contribution No. 861, Division of the Geological Sciences, California Institute of Technology, Pasadena, California.

Ink-writing recorder for quartz extensometer (*Hugo Benioff*)—A new recording system having high sensitivity and excellent stability characteristics has been developed for recording tidal strains and long-period earthquake waves with the fused quartz extensometer. The system uses a fixed carrier frequency of five mc coupled to two resonant circuits having tuning capacitors formed by a plate attached to the end of the quartz tube and two fixed plates. The resonant circuits are coupled to crystal diode rectifiers whose output drives an Esterline Angus ink-writing recorder. Two forms are being tested. At Isabella the oscillator employs a vacuum tube. At Dalton the oscillator is driven by transistors and the rectified output current is coupled to a double push-pull transistor cathode-follower circuit devised by L. Blayney, which drives the Esterline Angus recorder. The all-transistor circuit version operates for several months on a set of dry cells and is thus entirely independent of the power line.

Experimental long-period pendulum (*Ralph Gilman*)—An experimental horizontal pendulum involving an electrical period lengthening device has been tried. The method makes use of an auxiliary transducer of the moving-coil type. A steady current is passed through the coils, poled in such a way as to produce a negative restoring force. Long-term pendulum stability has been achieved at an 85-sec period. Records have been made with a 90-sec galvanometer giving a peak response in the neighborhood of 60 sec.

NEW RESULTS FROM LONG-PERIOD SEISMOGRAPHS (HUGO BENIOFF AND FRANK PRESS)

The following long-period instruments have been in operation at the Seismological Laboratory for almost a year: (1) a modified Benioff vertical reluctance seismometer, $T_0 = 2$ sec, $T_g = 180$ sec, (more recently $T_g = 600$ sec); (2) Press-Ewing vertical and horizontal seismographs, $T_0 =$ 30 sec, $T_g = 90$ sec. For wave periods greater than several minutes the responses are approximately the same, whereas for waves shorter than 30 sec the response of the Benioff instrument falls off more rapidly because of the capacitor. Using both types of instruments the following results have been achieved: (1) mantle Rayleigh waves and G waves are recorded frequently from earthquakes with magnitudes as small as 6½–7; (2) the gap in the dispersion curve connecting crustal and mantle Rayleigh waves has been filled; (3) relatively long-period body wave pulses ($T \geq 30$ sec) are clearly observed owing to the reduced response to the shorter period, continuing earthquake motion; (4) the impulsive initiation of the Rayleigh waves corresponding to the components of maximum group velocity is now frequently observed with a characteristic appearance which serves to identify the wave group at sight.

VELOCITY OF SEISMIC WAVES IN THE EARTH'S MANTLE (BENO GUTENBERG)

The Earth's mantle may be divided into four regions: (a) from the Mohorovicic discontinuity down to a depth of about 200 km with small changes in the wave velocities which may have minima in this range; (b) from 200 to 950 ± km with relatively rapid, fairly regular increase in velocity without discontinuity; (c) from 950 to 2700 ± km with smaller and less regular increase in velocity; almost straight-line portions of the travel-time curves and relatively small wave amplitudes in certain ranges of distance indicate that at least in two portions of this region the wave velocities increase relatively little with depth; (d) from 2700 km depth to the core boundary with little change in velocity and possibly slight decrease approaching the core.

ATTENTUATION OF SEISMIC WAVES IN THE EARTH'S MANTLE (BENO GUTENBERG)

P and S waves with periods of less than a second near the epicenters are not observed at distances near 20°. In contrast, the period distribution of P and S does not change noticeably between distances of about 25 and 100° where P waves with components as short as one second exist, while S rarely has periods of less than four seconds. Waves at these distances have traveled mainly at depths below about 200 km in the mantle. In this portion of the mantle the absorption coefficient k for amplitudes of P, PP, and S is about 0.06 per 1000 km regardless of T, contrasting with results from laboratory experiments and from amplitude studies of surface waves which indicate that k is approximately proportional to $1/T$. Thus, attenuation processes in the mantle below about 200 km differ from those in the crust. The complicated structure in the lower crust and upper mantle prevents calculation of k for these.

SPECTRUM OF P AND S IN RECORDS OF DISTANT EARTHQUAKES (BENO GUTENBERG)

In records of shallow and deep teleseisms written at Pasadena simultaneously by various short and long-period instruments, body waves show distinct wavelets with relatively large amplitudes a. Their periods T usually differ appreciably on records of instruments with different characteristics. In P, a/T has maximum values at one or two different periods between one and seven seconds; maxima of a/T decrease for $T > 7\pm$ sec. Similarly, in PP, maxima of a/T decrease for $T > 12 \pm$ sec. In S, different instruments give about equal maxima for one to three periods between about 4 and 20 sec, maxima of a/T decrease for $T > 20$ sec. Neither P nor S show measurable dispersion. Contrary earlier findings have been based on records of a single instrument and probably result from combining data for different successive phases, including P, pP, sP, PcP and waves reflected or refracted at shallow discontinuities. Relatively long trains of P-waves with periods of one or two seconds occur frequently together with single wavelets of longer periods and may result from scattering as suggested by Tatel. For magnitude determinations, P-waves with $T > 10$ sec and S-waves with $T > 20$ sec should be avoided.

THE 'BOUNDARY' OF THE EARTH'S INNER CORE (BENO GUTENBERG)

Unlike P and S through the mantle, PKIKP-waves with periods of about one second arrive up to 20 sec earlier than corresponding wavelets with periods of over $5\pm$ sec. If this difference results from disperison in a transition zone between outer and inner core, the calculated 'radius' of the inner core is over 100 km greater for short-period than for long-period waves, and there is probably a rapid but not discontinuous increase in viscosity from the outer to the inner core.

THE AFTERSHOCK SEQUENCE OF THE KAMCHATKA EARTHQUAKE OF NOVEMBER 4, 1952 (MARKUS BÅTH AND HUGO BENIOFF)

Aftershock epicenters of the Kamchatka earthquake of November 4, 1952, are distributed over an area approximately 1030 km in length by 240 km in width. Assuming that this distribution represents the active strain zone, the total average strain, average elastic energy, and average stress of the rocks before slip were 11.9×10^{-6}, 1.35×10^{2} ergs/cm^3 and 12.6 kg/cm^2 respectively. The fault movement was transcurrent and dextral.

The strain release curve of the sequence has been constructed using observations from Uppsala and Kiruna. The curve exhibits three segments each of the form $J^{\frac{1}{2}} = A + B \log t$, where J is the energy and t is the time measured from the time of the principal earthquake. The slope B changes abruptly at $t = 0.4$ days and at $t = 195$ days, the latter change being particularly pronounced. Moreover, this was accompanied by other evidence suggesting a change in mechanism. The aftershock activity has its highest concentration in the vicinity of the principal earthquake and tapers off toward both ends of the active fault segment. The rate of strain accumulation and release for the time interval from 1897 to 1956 for the entire Kamchatka - northern Japan stress system shows a slow decrease with time. Comparison of the rate of the entire system with that of the aftershock sequence leads to an approximate estimate of the possible duration of the sequence of 15 years.

MECHANISMS OF THE AFTERSHOCKS OF THE KERN COUNTY, CALIFORNIA, EARTHQUAKE OF 1952 (MARKUS BÅTH AND C. F. RICHTER)

Using directions of first motion of P at nearby stations, the orientation of fault traces and the nature of fault motions have been deduced for 57 aftershocks. Unlike the main shock, they exhibit considerable strike slip, left-hand dominating on and to the south of the White Wolf fault, right-hand to the north of it. The two last mentioned mechanisms represent a secondary strain release, beginning not earlier than 37 hr after the main shock.

EFFECT OF UNEQUAL FLING OF TWO SURFACES OF A FAULT (HUGO BENIOFF)

When a fault is also the contact between two rock masses having unequal elastic coefficients or when the constraints on the two blocks are unequal as in the case of a shallow dipping fault, the radiation pattern departs from the symmetrical form commonly assumed in fault plane solutions. Considering compressional waves, the nodal plane which in the case of equal elastic coefficients coincides with the fault plane, is rotated toward the block with the larger elastic coefficient or with the greater restraint. The orthogonal relationship between this nodal plane and the one normal to the fault plane which holds for those faults with equal fling of the two surfaces is in this case no longer valid. Recordings made by John Healy with Press' ultrasonic model assembly show deviations of at least 15°. Since many earthquakes occur at or near the continental margins where the continental crust meets the thinner oceanic crust, some of the difficulties found in fault-plane work may arise from the departure from orthogonal condition.

CIRCUMPACIFIC TECTONICS (HUGO BENIOFF)

The evidence from seismology and geology as to the tectonic characteristics of the circumpacific margins suggests that there are two principal movements taking place. These are characterized by (1) a tangential slip parallel to the margin of the oceanic mass relative to the continental mass, and (2) a smaller relative radial movement of the two domains responsible for the pronounced marginal relief and some additional auxiliary faulting. The tangential movement is such that the continents are rotating in a clockwise direction relative to the oceans, thus producing dextral transcurrent faulting at the margins. The evidence from the South American segment is not complete so that these conclusions are necessarily tentative.

TABLE 1 – *Corrections for magnitudes as function of wave periods relative to those at the Seismological Laboratory, Pasadena, (negative corrections indicate calculated magnitudes larger than for Pasadena)*

Location[a]	Component	Period, seconds					
		0.2	0.4	0.6	0.8	1.0	1.2
Mt. Wilson	NS, EW	−0.2	−0.2	−0.2	−0.1	−0.1	−0.1
Riverside	NS	−0.2	+0.1	+0.1	+0.2	+0.3	...
	EW	−0.1	+0.1	+0.1	+0.3	+0.4	...
La Jolla	NS	...	−0.3	−0.2	−0.1	0.0	0.0
	EW	...	−0.3	−0.2	−0.2	−0.1	−0.1
Santa Barbara	NS	...	−0.4	−0.3	−0.3	−0.3	−0.3
	EW	...	−0.4	−0.3	−0.3	−0.3	−0.3
Haiwee	NS	...	−0.5	−0.4	−0.3	−0.3	−0.3
	EW	...	−0.2	−0.2	−0.2	−0.2	−0.2
Tinemaha	NS	...	−0.6	−0.6	−0.5	−0.5	−0.5
	EW	...	−0.5	−0.5	−0.5	−0.3	...
El Centro	NS	...	−1.0	−0.8	−0.6	−0.6	−0.6
	EW	...	−1.0	−0.7	−0.6	−0.5	−0.5

[a] The stations at Pasadena, on Mt. Wilson and at Riverside are on granitic rock, Santa Barbara is on alluvium with boulders, Haiwee on tuff, Tinemaha on basalt, La Jolla on beach deposits, El Centro on alluvium.

MAGNITUDE CORRECTIONS AS FUNCTION OF THE WAVE PERIOD FOR STATIONS OF THE PASADENA NETWORK (BENO GUTENBERG)

Magnitude corrections relative to the magnitude found at the Pasadena Seismological Laboratory on bedrock have been determined as function of the period for stations of the Pasadena network equipped with torsion seismographs (Table 1). For records of the strong-motion torsion seismographs at El Centro, measured on the 8× film projector, 1.35 was added to the logarithm of the amplitudes.

The 'average' correction for the Seismological Laboratory (probably +0.2 for waves having periods $T < 10\pm$ sec, 0.1 for waves with longer periods) has to be subtracted from all corrections in Table 1 to find 'average' magnitudes.

SEISMIC ACTIVITY IN 1957 (BENO GUTENBERG AND C. F. RICHTER)

In 1957 seismic activity increased from the low level during 1954 to 1956 to about average. There were at least 20 shallow shocks of magnitude 7 or more. Probably four of them, (March 9 in the Aleutian Islands; June 27, NE of Lake Baikal; July 28 in Mexico; December 4 in Mongolia) were great earthquakes ($m > 7.3$, $M > 7.7$) but none exceeded $m = 7.7$ or $M = 8\frac{1}{4}$. About five shocks of intermediate depth had magnitudes of 7 or more; two of them were possibly great, on November 29 in South America and on December 17 in the New Hebrides. Two deep shocks (depths 600 and 650± km) had magnitudes of 7 or more (about $m = 7.2$).

ENERGY RELEASE IN EARTHQUAKES (BENO GUTENBERG)

On the assumption that the energy E of a shock of magnitude m is given by

$$\log E = 5.8 + 2.4\, m$$

Table 2 gives annual energy releases (preliminary magnitude determinations for 1957).

TABLE 2 – *Annual energy release in 10^{24} ergs*

Year	Focal depth, km			
	<60	60–300	>300	all
Average 1908/57	6.0	1.6	0.3	7.9
1954	0.9	0.5	0.1	1.5
1955	1.3	0.8	0.1	2.3
1956	1.2	0.5	0.3	2.0
1957	6.0	0.9	0.3	7.1

Geophysical Investigation of Mono Basin (Frank Press)

In a joint project with the Geophysics Branch of the U. S. Geological Survey (L. C. Pakiser) seismic and gravity measurements were made in the Mono Basin, California. Seismic refractions indicated sedimentary depths as great as 5500 ft. An extrapolation to the center of the basin using gravity observations indicates a maximum thickness of about 12,500 ft. This great depression seems to have occurred along near vertical faults bounding a triangular block.

Phase-Velocity Method of Crustal Exploration (Frank Press)

In a joint project with M. Ewing of Columbia University a Rayleigh wave phase velocity investigation of the United States was completed. Crustal thickness determined by this method was 40–50 km in the Basin Range province, 42–49 km in the Rocky Mountain region, 35–41 km in the Interior Plains, 40 km under the Appalachian Mountains. The work made use of seismograms of the Pacific earthquake of April 14, 1957.

Model Seismology (Frank Press and John Healy)

An experimental and theoretical study of the relation between absorption coefficients for compressional, shear, and Rayleigh waves in low-loss media was carried out. A theoretical relationship was derived and experimentally verified. A two-dimensional experimental study of compressional and Rayleigh waves transmitted along a slit, particularly the conversion of these waves after passing into the homogeneous material beyond the slit was carried out. It was found that the Rayleigh wave is the predominant source of energy propagating into the medium beyond by a mechanism of Rayleigh to shear conversion at the end of the slit.

Sediment Thickness on Sea Floor (Frank Press)

A study of sediment thickness in the eastern Pacific Ocean (east and north of Easter Island) by the Rayleigh wave dispersion method yields values from 0.3–0.6 km with an average of 0.5 km.

Visitors

The following visitors were resident at the Laboratory for limited periods: M. Båth, University, Uppsala; K. E. Bullen, University of Sydney; H. Menzel, University of Hamburg; Y. Satō, Earthquake Research Institute, Tokyo.

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Discussion of "The Columbus Geoid"

BY W. A. HEISKANEN

[*Trans.*, **38**, 841–848, 1957]

William M. Kaula (Army Map Service, Washington, D. C.)—The compilation of the Columbus Geoid has been a task of great magnitude and a valuable addition to our knowledge of the figure of the Earth. To extract the maximum benefit from gravity data for geoid computation, careful attention must be given in forming mean anomalies of areas both to the relationship of anomalies with topography, and to the correlation of anomalies with each other. The procedures used in computing the Columbus Geoid appear to take the topography into account very well, but the paper of Heiskanen is not explicit at some points where correlation of anomalies with each other is important:

(1) The method of estimating 1° square mean anomalies from the 5° × 5° maps is not precisely described.

(2) It is stated that maps of 1° square mean anomalies were used for interpolation and extrapolation of the gravity anomalies of the unsurveyed areas. If the coefficient of correlation used or implied in this extrapolation is incorrect, systematic distortions will result.

(3) The method of forming 5° square means from 1° square anomalies is not described. For 1° squares which have no observations, it is not stated whether zeros or extrapolated values are used, or whether they are entirely disregarded. Zeros will give 5° square mean anomalies systematically too small in absolute magnitude; disregard will cause the 5° means to be systematically too high.

(4) No mention is made as to whether any gravity data were rejected. It is hoped that none were (except for observational error), or, at least, that rejection criteria were not biased against any particular magnitudes.

(5) It is stated that the effect on ξ and η of areas beyond 3° has never been computed to be more than 4″, and of areas beyond 20°, never more than 2″. Considering how many areas have a mean anomaly assumed zero, these results are not surprising. With the present irregular coverage of gravity data, the only way accuracy of gravimetrically computed deflections can be estimated is indirectly, through the variance and covariance of gravity anomalies.

(6) It is stated that one observation cannot represent an area larger than 3° × 3°, and that zero is used for such areas. However, *Hirvonen* [1956] showed that the best value is the weighted mean of the observed anomaly and zero

$$\Delta g_s = \frac{G_s^2}{G_0^2}\Delta g_0$$

where G_s^2 is the variance of mean anomalies of squares of side length s, and G_0^2 is the variance of point anomalies. This rule applies to squares smaller than 3° × 3° as well, of course, and makes an appreciable difference down to less than 1° × 1°.

The use of spherical harmonics should not be condemned too hastily. Developments useful for such purposes as satellite perturbations should be obtainable from material already available, with proper techniques. Both *Jeffreys* [1941, 1943] and *Zhongolovich* [1952] committed errors which were not inherent in the harmonic method. Their principal mistake was in taking the 10° square mean anomalies to be the direct mean of those 1° square anomalies for which observed values were available. This procedure resulted in a pronounced correlation of the absolute magnitude of their 10° square mean anomalies with the number of observations on which they are based, as shown in Table 1.

The correlation is less marked for Zhongolovich's compilation than for Jeffreys', because Zhongolovich used all observations available within each 1° square, and because he omitted 25 10° square anomalies (without stating specific criteria for doing so).

Applying Hirvonen's weighting G_s^2/G_0^2, where $s = 10°/\sqrt{n}$, to Jeffreys' data reduces his rms 10° square anomaly to ± 16.3 mgal, and removes the correlation with n entirely; applying it to Zhongolovich's data reduces his rms to ± 13.0 mgal, but reverses the correlation for $n < 4$, indicating that his rejection criteria may have been biased against large magnitudes.

Zhongolovich's harmonic analysis also has questionable features in that (1) a third-degree

TABLE 1 – *Estimates of 10° square mean anomalies*

Number of 1° square values n	Jeffreys		Zhongolovich	
	Number of cases	Rms 10° square mean G_{10}°	Number of cases	Rms 10° square mean[a] G_{10}°
		mgal		mgal
1 to 14	149	±46.9	117	±26.9
15 to 30	38	40.6	34	26.4
31 to 60	31	24.3	35	20.6
61 to 100	3	19.4	18	16.5
1 to 100	221	±43.2	204	±25.1
Ratio of variances, $n \leqq 30/n > 30$	3.60		1.90	
One per cent significant ratio (Fisher z test)	1.99		1.76	

[a] Converted from Helmert to International Standard Gravity.

harmonic expression is used for the mean anomalies of 10° squares without observations, in computing the harmonics up to the eighth degree; and (2) all 10° square mean anomalies are weighted equally, to retain the convenience of orthogonality.

The Mapping and Charting Laboratory, Ohio State University, has issued a world map of mean free-air anomalies for 5° squares, dated December 28, 1956, which is presumably the basis for the Columbus Geoid. A total of 154 independent 10° square mean anomalies can be formed from blocks of four 5° square mean anomalies on this map. Applying the same analysis to these values shows a correlation with n in the opposite direction to Jeffreys' and Zhongolovich's as shown in Table 2.

These values raise a suspicion of either (1) too low a correlation coefficient in extrapolating 1° square mean anomalies; or (2) use of zeros for 1° squares in forming 5° square means; or (3) rejection criteria biased against large magnitudes. Note that Zhongolovich's ± 25.1/Heiskanen's ± 9.6 = 2.6, approximately the ratio by which Heiskanen states Zhongolovich's geoid undulations are "larger than the gravity observations permit."

TABLE 2 – *Estimates of 10° square mean anomalies*

Number of 1° square values n	Heiskanen	
	Number of cases	Rms 10° square mean G_{10}°
		mgal
1 to 14	23	±8.5
15 to 30	38	8.0
31 to 60	55	8.9
61 to 100	38	12.4
1 to 100	154	±9.6
Ratio of variances, $n > 60/n \leqq 60$	2.16	
One per cent significant ratio	1.79	

The Columbus Geoid is by far the best gravimetric geoid so far computed, and is a valuable guide for further developments. However, it not only must be regarded as a geoid of minimum undulations because of lack of data, but it also must be suspected of distortion; that is, of not being the most probable geoid on the basis of the available data. A more thorough harmonic and statistical analysis of the gravity field is needed before any major corrections of geodetic datums, etc., are made on the basis of gravimetrically computed geoid elements. In the past 25 years, there has been considerable development of techniques for analyzing stochastic processes, particularly stationary time series. Some of these techniques should be adaptable to analysis of the Earth's gravity field.

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W. A. Heiskanen (Institute of Geodesy, Photogrammetry and Cartography, Ohio State University; author's closure)—I am indeed glad that Kaula has written his comments to my paper. Through positive critique we further science a great deal. Kaula obviously could only comment generally on our methods, because it has not been possible for us, because of circumstances beyond our control, to publish details concerning our gravity field.

The main subject of our discussion is how far and in what way we can extend the gravity anomaly field to the unsurveyed areas from the observed gravity values. Kaula has essentially six comments to make.

(1) This comment is based upon an incorrect impression. We have not estimated the 1° square

anomalies from the 5° × 5° maps. Quite on the contrary, the 1° × 1° square maps have been our basic maps.

(2) In the interpolation and extrapolation of the gravity anomalies of the unsurveyed areas we have used not only mathematical but also physical correlation. The correlation factors change a great deal from one area to another; so that, in our opinion, the mathematical 'advice' alone is not adequate.

(3) We have not estimated the anomalies of 3° × 3° squares from 1° square anomalies. For 1° squares without any observations we have used interpolated anomalies except in the case where the squares are too far from any observed point. How far we can extrapolate depends essentially on the large scale variation of topography of the area in question. For instance, we can extrapolate along the belts of negative gravity anomalies rather far but perpendicular to the belt we cannot. The gravity observations at the ocean islands cannot be extrapolated except to the island itself and its shallow 'apron.' The mean anomalies of 5° × 5° squares have been computed on basis of the observed, interpolated and extrapolated gravity anomalies.

(4) We have not rejected any gravity observations, except old and rather unreliable measurements where we have been able to replace them by modern accurate observations.

(6) I will consider (6) first, because it is closely connected with (1)–(4). I confess that in this case my wording is misleading. We have, in fact, used in addition to the physical evidence also the weight factors obtained by Hirvonen. We have, however, been careful with them, because they have of course been computed on basis of the material of the continents and we have to apply them mostly on the oceans where the G_s and G_o differ from their continent values.

(5) The effect of the areas beyond 3° and 20° on the vertical deflection components ξ and η, respectively less than 4″ and 2″, is based on our practical computations. In some cases the effect might be higher, but we can, by selecting the computation points carefully, avoid a great deal of the unfavorable areas. By the way, our results are in rather good agreement with Figure 6 of *Kaula* [1957, p. 304] which reveals that the "rms error of gravimetrically computed deflections of the vertical due to errors of representation of point anomalies plus lack of gravity data beyond given radii" is, beyond 3°, about 3.7″ and beyond 20°, 1.7″. When we had gravity observations also beyond both these boundaries, it is no wonder that our ξ and η values never exceeded 4″ and 2″.

We have one principal difference in our opinions. Kaula seems to trust the mathematical analysis 100 pct, while we use the combined evidence of mathematics and physics. I have in earlier discussions let nature itself testify whether the opinion of my opponent or my own is closer to the truth. I am sure also in this case that if we venture to extrapolate the free-air gravity values, which are not sufficiently representative for too large unsurveyed areas, like the South Pacific, nature itself cannot follow us. I have time to wait for two or three years when we shall have observations also from the now unsurveyed areas, and when the comments raised by Kaula will no longer have more than slight significance. Then we can see whether the undulations of the Columbus Geoid are too small or not.

We are about to develop gravity anomalies using low-order spherical harmonics. So far we have not had time, because, in our opinion, it has been far more important to try to obtain material and analyze it. Without this preparatory work no adequate applications of the gravity anomalies to geodetic purposes is possible.

We will publish soon a comprehensive investigation in which all our methods will be described in detail. A new "edition" of the Columbus Geoid, on basis of the increased and isostatically reduced gravity anomalies, will be published next winter.

As far as I remember in the history of geodesy, no less than three famous mathematicians have made mistakes when they, in writing about geodetic subjects, separated their analysis too far from the physical facts. One was about 80 years ago, one 30 years ago, and one ten years ago; in two of these cases nature supported my opinion. As to this case, we do not know yet which of us, Kaula or me, is closer to the truth. If I am right, it is good; if my good former student, Kaula, is right, it is not too bad either. At least one of my prophecies is right. I mentioned [*Heiskanen*, 1957, p. 7] that Kaula is "a man-of-the-future in geodesy."

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Discussion of "Some Comments on the Results Obtained with the Cambridge Pendulum Apparatus in North America"

BY R. L. G. GILBERT

[*Trans.*, **38**, 457–461, 1957].

J. C. Dooley (Bureau of Mineral Resources, Geology and Geophysics, Melbourne, Australia)—The Cambridge pendulums were used in Australia by the Bureau of Mineral Resources, Geology and Geophysics during 1950–51. A statistical analysis has been made of the periods observed, and this will be published as part of a report on the survey. However, some of the conclusions reached are relevant to Gilbert's paper and to Garland's discussion.

In the Australian survey, six pendulums (1A, 1B, 1C, 6A, 6B and 6C) were used. Set 1 pendulums were used at Melbourne only; Set 6 were used at Melbourne and also at 58 field stations throughout Australia. A set of observations with one set of pendulums normally comprised two swings with pendulums A and B together, and two swings with pendulums A and C together. Six sets of observations were made at Melbourne with each set of pendulums, at intervals throughout the survey. A series of two or more swings with one pair of pendulums is referred to as a half-set of observations.

Analysis of the repeated observations leads to the following conclusions:

(1) The period of Pendulum A of either set varied according to whether it was swung with B or C, confirming *Cook's* [1954] observations.

(2) The variance of mean periods of a swing within a half-set was substantially less than would be expected from the variance of the individual periods of the pendulums. This indicates that motion of the support was an important factor, and that its effect on the periods was largely eliminated by taking the mean of two pendulums swung together.

(3) Pendulums 1C and 6C were generally more consistent than the average, and 1B was generally less consistent than the average. These differences in behavior were statistically significant in some groups of observations but not in all groups.

(4) The mean periods of Pendulums 1A-1C were significantly more consistent than the mean periods of other pairs of pendulums.

(5) The variance of individual periods of Set 6 for field work was generally not significantly greater than for base observations. There was no significant difference in the variance of the mean periods for field and base observations.

(6) The variance between the means of half-sets with different pendulum pairs was much greater than that estimated from the variance of means of swings. This was attributed to mechanical changes in the pendulums, or to magnetic effects.

(7) The repeated observations at Melbourne showed no systematic trend. The scatter of gravity values obtained was consistent with that estimated from the variance of means of half-sets.

(8) The difference between the periods of the pendulums of a set varied with time in a very erratic fashion. This appeared to be just as erratic for repeated observations at Melbourne as for field stations.

We agree with Garland that it would be unwise to rely on the results of one pendulum only. In particular, Pendulum 1B, which repeated best in the North American survey, was the worst in the Australian survey. It is not agreed that the adoption of an individual pendulum period is preferable to taking the mean period of a pair of pendulums swung simultaneously.

While it is true that comparison of the results of different pendulum pairs throws much light on the accuracy of the survey, it is agreed with Gilbert that repeated observations at a number of stations are highly desirable. Such observations afford the most direct means of investigating the mysteries of the behavior of pendulums, and lead to well established and accurate gravity values.

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R. L. G. Gilbert (Dominion Observatory, Ottawa; Author's closure)—The problem of dealing with data such as is obtained from pendulum measurements is complex; as Garland points out in his discussion published with the paper, we should not neglect the results from four out of five pendulums without reasons. I am sure he would agree that the results might properly be weighted and combined. This raises a nice problem, however, in that it is debatable whether the 'jumps' in periods of the pendulums occur sufficiently frequently for a statistical method to be applicable, because, by definition, statistics deal with random errors, not discrete jumps. For the same reason, it is not certain that his claim, that Chauvenet's criterion indicates that no results should be rejected, is valid. I had certainly overlooked the fact that the results from pendulums of Set 1 and those of Set 6 can give an estimate of error at the stations. However, my assumption that Pendulum 1B is stable is by no means *a priori* in any sense of the expression; there is no evidence of instability at any of the stations at which more than one measurement was made, throughout both years of the survey, and it seems illogical to suppose that the pendulum should be unstable at intermediate stations. The main purpose of my paper was to point out that the method usually employed in reducing pendulum observations is not the only one which may be used. The difference in the final gravity values found using all the pendulums and only 1B shows that values at the various sites should not be regarded as having an accuracy better than about one milligal; I expect that a similar analysis on the Gulf pendulum records would lead to a similar conclusion. It may be noted that pendulum 1B gives gravity differences between Ottawa, Washington, and Teddington in good agreement with those quoted by *Cook* [1957] as the result of an analysis of many different measurements.

I was most interested in Dooley's contribution; in the case of the measurements at Melbourne, it would seem that ground movements were much more severe than in North America, and the errors from this cause will tend to obscure those from other causes, when individual pendulum periods are considered. His results confirm my tentative conclusion that Pendulum 1B did not perform well in other surveys.

The cause of the random changes in period may be caused by differential thermal expansion between the knife-edge and the body of the pendulum; a certain amount of elastic deformation could be tolerated, after which mechanical slipping would take place. This mechanism could easily explain the variation in behavior of pendulums during different surveys, with different operators, and it would be interesting to see if any improvement were to result from keeping the pendulums at as uniform a temperature as possible at all times during a survey including transit between stations.

The paper and discussions are primarily debating the best manner in which statistics may be used in the evaluation of the pendulum results. It is agreed that so long as ground movements are small, the period of a single pendulum may be used; this was generally true in North America, but seemingly not true in Australia. We have five independent sets of observations, made with apparatus which appears to suffer from random jumps in 'zero reading.' Elementary statistical analysis shows that in North America four of these sets of observations are subject to jumps and one is not; the order of magnitude of the jumps are one milligal, and the expected accuracy of an observation is about 0.3 milligal. The best method of using the results is debatable; if the jumps were an order of magnitude larger, the four sets of observations subject to jumps would be rejected on any grounds; statistical methods are not rigorously valid either for rejecting or for weighting the several sets of results, but it is clear that the sets of observations which are subject to jumps will have but little weight compared to the other. The only definite conclusions which can be drawn are that final results should not be adopted to closer than the nearest milligal, and that investigations are urgently needed to find the cause of the 'jumps' in the periods of the pendulums.

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Discussion of "A Probe for Measurement of Thermal Conductivity of Frozen Soils in Place"

BY ARTHUR H. LACHENBRUCH

[*Trans.*, **38**, 691–697, 1957]

William Woodside (Division of Building Research, National Research Council, Ottawa, Canada)—The author has suggested a modification in probe design which he expects will enable the simultaneous determination of both thermal conductivity and thermal diffusivity. However, it appears that the thermal diffusivity may be estimated from data obtained with the present type of probe.

In the notation used in the paper, (1) with the time correction t_0 reads

$$\Theta(a, t) = \frac{q}{4\pi K}\left[\ln\frac{4\alpha}{\gamma a^2} + \ln(t + t_0)\right] \text{ for } t \gg \frac{a^2}{4\alpha} \qquad (9)$$

When $\ln(t + t_0) = 0$, let the value of the temperature rise be given by $\Theta(a, t) = \Theta_0$.

Then $\Theta_0 = (q/4\pi K)\ln(4\alpha/\gamma a^2)$ or

$$\alpha = \frac{\gamma a^2}{4}\exp\left(\frac{4\pi K}{q}\Theta_0\right) \qquad (10)$$

Since the values of $(4\pi K/q)$ and Θ_0 may be obtained from the corrected plot of temperature versus logarithm of time, the thermal diffusivity α of the test material may be evaluated, providing the value of a, the distance of the point of temperature measurement from the axis, is known for the probe in question ($\ln \gamma$ is Euler's constant which is 0.577). For the probe described, the value of a is probably known with fair accuracy. However, should the value of a not be known, it could be determined by inserting the probe in a material of known thermal diffusivity and performing a normal test.

The advantage of the above simple procedure for obtaining thermal diffusivity is that it may be applied to the data already obtained from the several hundred probe tests performed by the author, whereas the author's suggested modification to the probe design involves the repetition of these tests.

Arthur H. Lachenbruch (U. S. Geological Survey, Menlo Park, Calif., Author's closure)—I find two objections to Woodside's proposal. First, the equation given by him is valid, if at all, only for large t. In the present application this condition is not adequately fulfilled when $\ln(t + t_0) = 0$, and hence the equation cannot be used to represent Θ_0. We could, however, retain $\ln(t + t_0)$ and calculate the constant term using the observed value of temperature rise for say $t + t_0 = 1000$ sec. Even in this case however, we would not be justified in identifying the constant term with

$$(q/4\pi K)\ln(4\alpha/\gamma a^2)$$

because of the departure of the present probe from the mathematical model. This point constitutes the second objection.

As an illustration of the second point, consider the effect of contact resistance between the inner copper tube and the outer brass tube. Although the contact resistance at the outer probe surface can probably be neglected in this work, the effect at the interior interface is expected to be appreciable. By a slight modification of a result given by *Blackwell* [1954, Eq. 22] it can be shown that taking account of this effect changes the constant term to

$$(q/4\pi K)\ln(4\alpha/\gamma a^2) + (q/2\pi)(1/pH)$$

where p is the internal radius of the brass tube and H is the contact resistance. (Note that the correction term depends only on the properties of the probe.) The same effect leads to the following revised expression for ϵ (Eq. 7b of my paper) to the second term in η

$$\epsilon = -\eta[\ln\eta]\tfrac{1}{2}S - \eta[\tfrac{1}{2} + 0.10S] + \frac{a^2 c_0}{pH}\frac{1}{t} + \cdots \qquad (11)$$

Thus to this degree of approximation at least, t_0 is shifted by a constant amount independent of the test medium. If this contact resistance represented the only departure from the mathematical model, we could evaluate both α and H from a knowledge of t_0 and K by using the following two independent relations obtained from the large-time solution

$$t_0 \approx t_\epsilon \qquad (12)$$

$$\Theta \approx \frac{q}{4\pi K}\left[\ln\frac{4\alpha}{\gamma_a{}^2} + \frac{2K}{pH} + \ln(t + t_0)\right] \qquad (13)$$

where ϵ is modified to take account of H. Eq. (12) is applied in the manner described for (8), and in (13) we use the observed temperature rise corresponding to a large value of $t + t_0$. Alternatively we could determine H from a test in a medium of known diffusivity.

Analysis of the data reveals that at least one other important general departure from the mathematical model exists. This is probably the effect of low diffusivity in the insulating tubing.

There is another source of departure that might be expected in coarse-grained media that should be kept in mind in any refined interpretation of probe data. For early times, when appreciable amounts of heat have penetrated the medium only to distances on the order of the grain diameter, the aggregate will present a 'parallel thermal circuit' [*Birch* and *Clark*, 1940, p. 625] and a quite different effective thermal conductivity than that of the 'series-circuit' conductivity presented for large values of time. The latter is generally identified with the bulk thermal conductivity of an aggregate. With each added complication we can expect the labor required in determining the diffusivity to increase and the accuracy of the determination to decrease. A more detailed study of the present probe is planned in order that optimum use can be made of the many data obtained with it. However, I do not expect this probe design to yield diffusivities as reliable as those obtained by independent measurement of specific heat and bulk density. On the other hand, the theory provides a needed guide to the use of t_0 in determining conductivities.

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Discussion of "The Statistical Treatment of Flood Flows"

BY P. A. P. MORAN

[*Trans.*, **38**, 519–523, 1957].

E. J. Gumbel (Columbia University, New York, received, Dec. 16, 1957)—Most statistical theories are based on the assumption that the observations are independent. In reality, most statistical observations are not independent. Still statistical methods continue to be used and often with a certain success. This may be because dependent observations follow statistical laws not too different from the independent ones. Therefore schemes developed for independent observations may under certain conditions also hold for dependent observations, especially if the dependence decreases with increasing distance between the ordered values. In the study of floods, the 365 daily observations during a year are not independent. The number of such observations is certainly less than 365.

Instead of the largest annual discharge, Moran uses the largest of the mean monthly observations. Thus, the number of observations from which the largest one is taken shrinks from 365 to 12. But this procedure does not result in independence, although the linkage between consecutive months may be weaker than that between consecutive days. In addition, the month with the largest mean may not be the month with the largest daily discharge. The procedure of taking the mean monthly discharge levels off the largest fluctuations. Therefore the safety of a structure which provides for this maximum may be insufficient.

We are not completely free in the choice of distributions to be used in a statistical analysis. The fact that we obtain a good fit, whatever this means, is a necessary but not sufficient criterion for the validity of such an hypothesis, since we can always devise formulas which will reproduce the observations exactly. However in such cases the formula takes its revenge for the constraint and the extrapolation may lead to fantastic results which nobody will accept.

Therefore *a priori* reasons are needed for the acceptance of a formula. Why should the distribution of the floods be logarithmically normal or of Pearson's type III? No *a priori* reason has been given by Moran and probably no such reason exists. The fact that the observed distribution is skewed to the left, a property of these two distributions, is not a sufficient reason since other such distributions exist. Behind the use of the lognormal distribution is hidden the assumption that first of all everything should be normal and second that if this does not hold every distribution can be reduced to the normal one by a logarithmic transformation, a statement which of course is erroneous.

By definition, floods are largest values. The distribution of largest values depends on the properties of the upper tail of the initial distribution of the discharges. The extremes are independent of the values occurring in the middle of the distribution and they are independent of each other except for the systematic climatic changes which may be neglected for the short intervals considered. The theory of extreme values as applied to the flood has a logical superiority: the floods are extremes. Therefore the asymptotic distributions of extreme values stand on a higher logical level in their use for floods than purely empirical procedures.

For the comparison between theory and observation Moran uses the χ^2 test. For a continuous variate this method requires two choices, the number of cells and the starting point of the division. The number of cells determines the numbers of degrees of freedom and this influence is known and can be eliminated. However the influence of the starting point is unknown and cannot be eliminated. In a previous paper [*Gumbel*, 1943] a numerical example has been shown where the probability $P(\chi^2)$ may vary from 0.02 to 0.70 according to the starting point chosen, and for the same observations, the same theory, the same values of the parameters and the same number of cells. To eliminate such catastrophes it is advisable to use the χ^2 test not for cells of equal differences of the variate but for cells of equal differences of probability. Then the starting point is fixed and its influence is eliminated. However, in its usual form, the χ^2 test is unreliable for a continuous variable.

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G. N. Alexander (U. S. Geological Survey, Washington, D. C., received Jan. 31, 1958)—Hydrologists concerned with the application of statistical methods to the estimation of floods are indebted to the author for devoting his statistical talents to hydrology. This discussion will be concerned primarily with the methodology rather than the mathematics of the problem. We seek the most suitable mathematical model for answering questions concerning the frequency of occurrence of rare floods. Confusion of thought, referred to by the author, often arises because the questions have not been specifically framed. One obvious question is: What is the best estimate of the frequency (expressed in terms of probability or its reciprocal using a time scale, namely, the return period) of a flood of magnitude greater than U occurring during the life L of a dam, given n years of flood data?

The paper by the author helps to answer this question, by giving 'efficient' methods for fitting the log-normal and Pearson Type III curves to observed data, and showing methods of obtaining their confidence limits. This statistical procedure involves three steps: (1) selection of distribution type; (2) estimation of parameters from the observations; and (3) determining the error in the estimates by means of confidence limits.

It is not essential to follow this routine. We may dispense with the first step and estimate parameters graphically using an 'eye-fit', we may obtain distribution-free confidence limits which are independent of assumptions concerning the distribution type.

The usual justification for fitting a distribution to a set of observations is that better estimates of the parameters are obtained and extrapolation is facilitated. However, linearity in a sample as shown on a graphical relation between flood magnitude x and the return period T is no criterion for determining how well the sample represents the population. In such cases confidence limits are really more essential than where discontinuities or 'kinks' give a warning signal. Hence it is considered that the selection of distribution type which dominated the early discussions still occupies a place of undue importance in the problem as a whole. It is high time that the effect of sampling errors as indicated by confidence limits were better understood. Nevertheless some comments on type selection are in order.

Selection of distribution type—The author states: "the form of the distribution (of floods) is not known and must be guessed." This is true in an individual case owing to sampling errors masking the differences shown by different types. However as with other variables, examination of a sufficient number of independent samples helps in the selection of type and also indicates the range that the variance can take. Hydrologists often select the type from the appearance of the observed distributions of the samples on probability paper. Partly because of the availability of extreme value (Gumbel-Powell) and log-probability paper these two have been used in practice almost exclusively if a distribution is assumed. It would appear that probability paper could be constructed for testing graphically other distributions provided such a distribution has a constant skewness either using the original variate or one obtained by transformation. Since a relatively short record is available, a large error in skewness is common, and it is doubtful whether it is worth considering other types of distribution for floods, at least for practical purposes.

The writer endorses the *a priori* arguments summarized by the author against the acceptance of Gumbel's distribution for floods, but these arguments are not relevant if the distribution is judged by the preferred *a posteriori* criterion of goodness of fit. *A priori* arguments, based on the central limit theorem have been used by *Chow* [1954] to support the claims of the log-normal distribution. Again such arguments are not really relevant to finite samples. An analysis has been undertaken by *Beard* [1954] on the flood distribution of a large number of rivers in the United States based on data of the U. S. Geological Survey. This analysis suggests that in a high proportion of cases the distribution approaches the log-normal, with a mean skewness greater than that required by the Gumbel distribution. Fortunately the log-normal is mathematically more amenable than the Gumbel distribution and there is much to be said in its favor for flood flows.

Estimation of parameters—The author has made some categoric statements regarding the methods of estimating parameters, criticizing graphical methods because of their inefficiency and the ambiguity associated with the 'plotting position.' In view of the sampling errors, the efficiency of mathematical methods is more apparent than real, and graphical methods are often justified in practical applications on the grounds of expediency. Also, if no distribution is assumed, then parameters such as the estimated 50-year flood are only obtainable by graphical means.

As a modern statistician the author prefers the method of 'maximum likelihood' for parameter estimation. This may be more 'efficient' over the range of observations but the 'method of moments' by automatically weighting the upper values may have advantages particularly if a straight-line is fitted to facilitate extrapolation. It should be recognized that there is no absolute criterion for the selection of method of fitting.

The author states: "The correct method of fitting a log-normal distribution is to take the logarithms of the observations and use their observed mean and standard deviation as estimates of the distribution parameters." The meaning of this statement depends on the interpretation of the word 'correct.' Admittedly this method is the simplest and if we have a normal distribution (of the logarithms) conclusions dependent on normality are strictly valid. The above discussion on methods is however more of 'academic' interest than of practical importance because of sampling errors.

Confidence limits—The author employs the Neyman-Pearson concept of confidence intervals for the estimates of the 100-year and 1000-year floods. As this discussion concerns methodology it is pertinent to examine this process for rigor and convention. The process envisages repeated sampling from a population whose parameters are usually (but not necessarily) estimated from the observed sample. By this means a (fiducial) probability is obtained that a specified range or interval covers the 'true' value of the population from which the sample was drawn. Considered graphically, this value will lie within a band whose width at any assigned return period T is a function of the fiducial probability P_f, the sample size n, the sample standard deviation s of the annual floods, and the type of sampling distribution assumed for the T-year flood. Note that the distribution of the T-year flood is not necessarily the same as the distribution of the annual floods. T is any positive integer.

This concept is very useful to employ with hydrologic time series for we have only one sample of the population observed whose length n is virtually limited by the length of record. Attempts to reduce the sampling errors by effectively increasing n by introducing other samples run the risk of being wrecked on the Scylla of nonhomogeneity or the Charybdis of correlation.

Of particular interest in the construction of confidence limits is the effect of n. Theoretically as $n \rightarrow \infty$ the confidence interval $\rightarrow 0$, but the approach is fairly slow, the width being inversely proportional to $n^{1/2}$. Thus, if n were increased from 50 to 200 the band would still be half as wide, and if n were reduced from 50 to 25 it would be about 70 pct wider; wide enough to contain many of the 'kinks' that are often ascribed to a change in the regime.

It is the usual practice to locate the confidence interval by using the observed sample to centralize it. This however is best regarded as a convention, for there is nothing in the confidence limit model requiring it and intuition suggests that one sample is of little value in locating the band. The ambiguities, associated with the plotting position referred to by the author are no greater than those concerned with locating the confidence band. Conventions are sometimes desirable to give consistency to results, but estimates so obtained are relative and not absolute.

If we have no absolute criterion for locating the confidence band, it follows that we cannot make precise probability statements concerning the location of the 'true' value within the interval. This is not necessarily incompatible with the conviction that at some stage the frequency of a flood decreases as its magnitude increases; it merely says that we do not know at what stage this decrease in frequency commences.

The author has demonstrated a method for computing confidence limits for the log-normal and type III distributions. The procedure given for the log-normal is identical with that which could be used with a normal distribution except that a transformation is required to log-units at the outset and the analysis is completed with a re-transformation to the original units. As the author states the confidence limits so obtained imply that the distribution of the T-year flood is log-normal.

In deriving confidence limits for Type III, the author assumes in effect that the distribution of the T-year flood is normal, and obtains confidence intervals which, for T greater than 100, are only about half as great as those for the log-normal. It appears that the comparative narrowness of the confidence band of the floods for the Type III distribution is partly accounted for by the lower estimate of the true value given by the Type III.

It is clear from the formula that the width of the confidence band for the log-normal for a given confidence coefficient and return period is proportional to $s/n^{1/2}$. As s is measured by the slope of the graph ($\tan \theta$) on log-probability paper, the width of the confidence band measured horizontally (for given T) is independent of s.

A graphical comparison of the horizontal width of the confidence bands for the log-normal and Type III for a given T and confidence coefficient shows that the difference between the two widths is small.

This suggests the possibility of estimating 'distribution-free' confidence limits for the factor t in the equation $x = \bar{x} + t \cdot s$. This factor, termed the reduced variate by the statistician, and the frequency factor by the hydrologist, has a distribution known as the non-central t.

Extensive tables by *Resnikoff* and *Lieberman* [1957] of the non-central t have been recently published which considerably facilitate the practical determination of its confidence limits. Strictly their use has the same limitations as in the 'central' t-test; if the variable can be normalized as in the log-normal distribution, this requirement is met.

Beard [1955] gave a method for obtaining confidence limits (for the log-normal) which according to his closure, he believes to be more precise than the non-central t. However, it gives intervals much wider than those found by the author, whose results accord closely with those using the published non-central t tables.

Application—We now return to the questions asked at the beginning of this discussion: What is the probability of a flood of magnitude greater than U occurring during a period L, given n years of record.

Following the author's procedure we can obtain an estimate X say, of the L-year flood from a fitted distribution of the annual floods. Then using the confidence limit procedure 'in reverse' we can estimate the risk α, that is, $\frac{1}{2}(1 -$ confidence coefficient), associated with the half-interval $U - X$. Then α gives the risk, or fiducial probability, of the 'true' L-year flood being greater than U. This gives an answer, but may be regarded as an error of the third type, to use Kimball's phrase, as it is the right answer but not to the question asked. It should be noted that for given U, the value of α is dependent, inter alia, on n, and hence not obtainable by extrapolation of the fitted line which is independent of n. To answer the specific question, we have to consider the distribution of the return period.

The author has given in his Eq. (2) the density function for the random variable T, whose mean value is P^{-1}. (Note that in the notation of (2), which we follow below, P is the mean frequency associated with the upper tail, and n is any number, not necessarily the number of years of observation.)

The probability of T being *less* than n is by the compound probability law simply given by

$$\Pr(T < n) = 1 - \Pr(T > n) = 1 - (1 - P)^n \qquad (12)$$

In this connection we require the probability of the flood occurring in a period of L years. Hence, $n = L$. Also the floods greater than U can be regarded as belonging to a population of floods whose mean return period is L years and whose risk of occurrence is α. Hence, the appropriate value of P to use in (12), is that corresponding to a mean return period L, hence, $P = 1/L$ and we have

$$\Pr(T < L) = 1 - (1 - 1/L)^L = 1 - e^{-1} = 0.63. \qquad (13)$$

It is believed that this probability is independent of the risk α but the solution to the problem of their simultaneous distribution will be left to the author.

At the close of his paper, the author using nonparametric methods, gives the value of $n + 1$ as the estimated mean return period for floods greater than those observed. He then goes on to say, "We cannot obtain in this way statements involving probabilities less than $(n + 1)^{-1}$. However, it is a curious fact if the true distribution is a logarithmic-normal one we can extend this idea to make a similar exact probability statement about x corresponding to any level of probabilities."

This appears to put the log-normal in a unique position, but this is not so: if the true distribution is known we can make statements at any probability level. In conclusion, this discussion goes at times outside the domain of the author's paper in the hope that he will maintain his interest in this inviting field of statistical hydrology.

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P. A. P. Moran (Dept. of Statistics, Australian National University, Canberra, Australia; Author's closure)—In reply to Gumbel, the purpose of the paper was to show that rather different distributions can fit the observed data equally well and give quite different estimates of the probabilities of given extreme values. The log-normal and Type-III distributions were chosen as examples for their ease of fitting and no assumption of normality, concealed or not, is made. Gumbel's distribution is harder to fit and is known, in the case of extremes from some distributions, not to fit unless astronomically large samples are used. The χ^2 test was not used dogmatically; simple inspection of Table 1 shows that both distributions used are good fits to the observations. The main point of the paper is to emphasize how uncertain estimates of flood probabilities are.

In reply to Alexander, one of the advantages of using statistical theory in fitting distributions is that it enables one to estimate the uncertainty in the parameters of the distribution. The method of fitting the log-normal distribution is 'correct' because the quantities used are jointly 'sufficient' estimators. The author does not admit the validity of any arguments based on 'fiducial' probability. Alexander's last statement about the log-normal is not correct. The log-normal distribution belongs to a small class of distributions for which it is possible to make probability statements of the particular kind considered at the end of the paper, without knowing the parameters of the distribution.

Discussion of "Water and Drainage in Semi-Arid Countries"

by Alfred Loehnberg

[*Trans.*, **38**, 501–510, 1957]

Raphael G. Kazmann (Stuttgart, Arkansas)—This paper is an excellent guide to water policy and seems to have a broader application than the author may have intended. If we define drought or aridity in terms of periods when demand exceeds supply, rather than in terms of minimum annual precipitation, the applicability of the author's remarks are greatly and legitimately extended. For all practical purposes droughts become economic problems rather than climatological: If the user can afford to pay for water, the water can be supplied. It is in suggesting a rational general procedure for producing water in the cheapest way by taking advantage of the geological environment, that the author has made a significant contribution.

The author's proposed method of procedure is sound engineering: Expend effort (and funds) in the direction of greatest ultimate return. However the assumption that agriculture is the best use for the water is open to argument. Recent authoritative evaluations of the utility of water have arrived at other conclusions. *Koenig* [1956, p. 328] of the Southwest Research Institute has stated:

> "I submit the proposition that the use of irrigation in the arid lands of the twentieth century is not an appropriate use of that valuable resource, water, but is an attempt to follow a historical precedent and increase the value of the land. Actually from the standpoint of water use, agriculture is a marginal use of water. In the United States the water that will support one worker in arid land agriculture will support about 60 workers in industry."

Moreover the author takes for granted that the engineering applicability of artificial recharge through wells is a fact. The problem of technique has been solved. But the engineering problem, how to accomplish artificial recharge cheaply enough for use by agriculture, still awaits a satisfactory answer. The situation is analogous to the problem of saline water conversion, it can be done, but it costs too much at present to be competitive even as regards water for most industrial or municipal purposes. Thus, at present at least, the assumption that large-scale artificial recharge will be practiced as part of a scheme to supply agricultural water in arid areas, is a somewhat questionable one.

These minor reservations should not overshadow the merit of the author's work. This paper is, I believe, the first one that the AGU has published which has placed flood control and drainage in proper perspective in the picture of water-resource development. It would be interesting and desirable, were other non-consumptive uses of water such as navigation, hydro-power, sewage disposal, and recreation, also evaluated and classified as to their roles in the overall picture of water utilization.

There is need for additional thinking along the lines pioneered by the author not only for 'semi-arid' areas but for all areas. Broad feasibility studies of water utilization, placing emphasis on the maximum consumptive use of water are presently lacking. New advances resulting from the intensive study of water have not been reflected in the approach to water resources development.

How many hydrologists realize, for example, the implications of the recent statement by *Rodebush* [1957, p. 7] that the free energy dissipated when fresh water in a river flows into the sea and loses its identity is equivalent to 1000 ft of head? It points to the distinct possibility that within 50 to 100 years the use of fresh water for the disposal of wastes will be uneconomic in many areas: possibly small amounts of sea water will be pumped inland and used as the vehicle for waste disposal while the fresh water is consumed.

Broad policy papers are urgently needed to tie in and interpret the volumes of stream flow, ground-water, hydrogeological, waste disposal, navigation, and other data now being amassed at an ever-increasing rate. The author is to be highly commended in having broken new ground in the theory of applied hydrology. Others should join him in developing the theory of co-ordinated and reasonable water-resource development.

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Alfred Loehnberg (Instituto de Ciencia Aplicada, Cuidad Universitaria, México 20, D. F., Mexico; Author's closure)—In the United States the utility of water for irrigation may be in doubt in certain regions. Most other national territories, however, stretched over the arid girdle, do not possess alternative agricultural regions in a humid climate with high productivity and efficient transport facilities for their products. The arid countries bordering the middle seas, for example, must practice irrigation to feed their peoples because one half to four fifths of their territories do not obtain sufficient rain to sustain even one safe crop per year. To imagine a high degree of industrialization for the Sudan and Egypt without extensive (and improved) irrigation is impossible. Mexico's future industrialization will, to a considerable degree, be based on irrigated industrial crops on parts of the arid and semi-arid terrains, which comprise 82 pct of the country's area. Excess of water in some of the remaining rain-plagued portions of Mexico is so great, that it justifies long-distance water transportation for urban and agricultural use alike.

The utility of water for several claimants in the presence of limited resources cannot be decided on financial calculations alone, but will increasingly have to be co-determined by social evaluation [*Loehnberg*, 1958].

Artificial recharge through wells for agricultural purposes is already practiced and is gaining ground. Mekoroth, Israel's public water company, carries out the procedures on a considerable scale in the plain of Lydda. Recharge of wells with surplus from spring flows during the rainy season should prove economical almost anywhere. An increase in application will depend as much on water engineers and hydrologists, being capable of demonstrating and calculating the feasibility of recharge for irrigation under given circumstances, as on further progress being made in the rentability of recharge techniques.

Kazmann's proposal to intensify work on the theory of coordinated water-resource development has the author's full support.

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Discussion of "Some Problems in Non-Artesian Ground-Water Flow"

BY P. WILH. WERNER

[*Trans.*, **38**, 511-518, 1957]

M. Maasland (Kansas River Projects, Bureau of Reclamation, McCook, Nebraska)—An interesting series of ground-water flow problems is considered in this paper. It is encouraging to note that not all investigators have lost an awareness of the value of the Dupuit-Forchheimer assumptions for the study of this type of problems.

Ever since the condemnation by *Muskat* [1937, pp. 303–318], the indiscriminate criticism of these assumptions has become quite general. Muskat ignores the more balanced review by *Dachler* [1936, pp. 27–32; 88–98] and asserts that the Dupuit-Forchheimer assumptions are invalid because they neglect the flow components in the vertical direction as well as variations of the horizontal velocity in the vertical plane, and because the errors so introduced cannot be bounded. Both criticisms are serious and valid for certain conditions, and more exact solutions for various problems will be helpful in delineating the applicability of these assumptions. The inconsistencies that have arisen are not due to the assumptions but rather to the fact that they have been used for solving problems to which they do not apply.

The hydraulics of wells placed in water-table aquifers has been extensively studied [*Zee* and others, 1955; *Nahrgang*, 1956; *Peterson*, 1955, *Schneebeli*, 1956] and it has been found that the Dupuit theory gives a reliable formula for the discharge and that it gives a fair description of the shape of the water table, except in the immediate vicinity of the pumping well. For the type of problems considered by Werner, a recent analysis by *Engelund* [1951, p. 20] indicates satisfactory agreement between results from the Dupuit and more exact theory. When applicable, the Dupuit-Forchheimer assumptions are particularly useful for the study of transient problems, as it would be very difficult to obtain analytical solutions for this type of problems for more comprehensive initial and boundary conditions.

Scheidegger [1957] expresses surprise when noting that the above assumptions are still widely used for engineering calculations and repeats the criticisms of *Muskat* [1937].

The engineer deals with a great variety of field problems and is seldom so optimistic as to imagine that the complexity of field conditions can be encompassed in a mathematical theory simple enough to be usable in his computations. The reason why he uses a simple theory is that it leads to results that are sufficiently accurate for the intended purpose.

In the following, the nature of the assumptions will be briefly outlined. Furthermore, a different definition will be proposed for the coefficient of recharge p which would seem more consistent with that used in current literature [for example, *Jacob*, 1943; *Engelund*, 1951]. Some difficulties encountered in using results derived from the linearized Boussinesq equation will be indicated.

According to the Dupuit assumptions we may write the following formula for approximately horizontally directed flow over a horizontal impermeable layer

$$q = -cz\,(\partial z/\partial x) \tag{19}$$

where

x = horizontal coordinate (dimension, L)
z = vertical coordinate (dimension, L)
c = hydraulic conductivity (dimensions, LT^{-1})
q = discharge (dimensions, L^2T^{-1}; when multiplied with the unit length in the direction perpendicular to the xz plane, the dimensions are L^3T^{-1})

Eq. (19) is derived on the assumption that the velocity component at the water table is a measure of the average horizontal velocity in the vertical cross section below the water table [see *Dachler*, 1936, for a useful discussion of (19) and (20)]. *Boussinesq* [1877] extended this assumption and applied it also to a moderately sloping impermeable layer and wrote

$$q = czI = cz\left(\alpha - \frac{\partial z}{\partial x}\right) \tag{20}$$

where α is the slope of the impermeable layer.

Note that the impermeable layer slopes downward with increasing x. Observe also that x is measured in the horizontal direction and that z is measured in the direction perpendicular to the horizontal but that the height z is measured from the sloping impermeable layer.

It is tacitly assumed that α is small. If the water table is parallel to the sloping impermeable layer, it follows from Figure 3 and Eq. (20) that $q_p = cz_0\alpha$. Consideration of the elementary problem of flow parallel to the impermeable layer shows that $q_p = ct \sin a$, in which t is the depth of the ground water measured in the direction perpendicular to the sloping impermeable bottom. As $t = z_0 \cos a$, we may write from the latter formula $q_p = cz_0 \sin a \cos a = \frac{1}{2} cz_0 \sin 2a$. Since for small values of a the sine doubles when a doubles, it follows that (20) will be very nearly correct for parallel flow if we put $\alpha = \sin a$. However, if we derive the gradient I using Eq. (20) from the detail of Figure 3, it follows that $\alpha = \tan a$. This difficulty arises because, by using the Dupuit assumptions, we do not calculate the flow parallel to the sloping impermeable layer, but rather the flow in the horizontal direction. It is therefore imperative that the application of all equations derived from (20) be restricted to problems involving small gradients of the impermeable layer in which case $\sin a \approx \tan a$. The formulas are not suited for the calculation of details other than the discharge and the height of the water table. The formulas derive their usefulness from the fact that these factors are of major importance in most engineering problems.

It is significant to note that Werner restricts the use of his equations and indicates that his formula (I.1.4) is valid subject to (I.1.5) being reasonably constant for various values of x.

Let us now differentiate (20) with regard to x, in which case we find:

$$\partial q/\partial x = c\alpha \frac{\partial z}{\partial x} - c\left[z \frac{\partial^2 z}{\partial x^2} + \left(\frac{\partial z}{\partial x}\right)^2 \right] \quad (21)$$

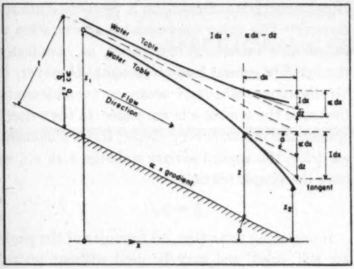

FIG. 3– Dupuit assumptions for flow over a moderately sloping impermeable layer

If there is a steady rate of replenishment p from the ground surface with which the water table is in static equilibrium, then $\partial q/\partial x = p$; since in this case q in (20) may be written as $q = p(x - a) + q_1$, in which a = the horizontal distance of the ground water divide from the z-axis, and q_1 is a component that depends on whether or not there is flow through the aquifer from one reservoir to the other (in Werner's terminology: 'original base flow'). Because of the nature of the Dupuit-Forchheimer assumptions we find that $q_1 = 0$ for $0 < a < L$, L being the width of the aquifer between the two reservoirs measured in the horizontal direction. If there is a constant rate of replenishment p with which the water table is not in static equilibrium, then $\partial q/\partial x = p - \epsilon(\partial z/\partial t)$, in which ϵ denotes the effective porosity. If these results are combined we obtain from (21) the following:

$$\frac{c}{\epsilon}\left[z \frac{\partial^2 z}{\partial x^2} + \left(\frac{\partial z}{\partial x}\right)^2 \right] - c\frac{\alpha}{\epsilon}\frac{\partial z}{\partial x} = \frac{\partial z}{\partial t} - \frac{p}{\epsilon} \quad (22)$$

which differs from (1) of Werner in that the last term is not p but p/ϵ. This is due to a difference in the definition of the factor p. As used here, it signifies the amount of surface applied recharge per unit area and per unit time, which definition is analogous to that of soil permeability. Werner defines (p/ϵ) as the speed of replenishment, and interprets it as a velocity of movement. However, the actual average velocity of movement of the water within the soil is a complicated function of the total porosity and the pore-size distribution, which function is not necessarily closely related to the effective or 'drainable' porosity. Apart from the fact that there is no apparent need to introduce a concept of dubious physical meaning, there is also the important consideration that for steady-state flow problems (constant p), knowledge of the effective porosity is not required. It would seem inadvisable to introduce factors in steady-state equations that are not relevant to the problem at hand.

Using the above definition of p, we find that the factor P in Werner's equations is equal to $2p/c$. Except for the change in P indicated, all his derivations and formulas remain unaltered because the division of the constant p by the constant ϵ does not change the nature of the basic differential equation.

Attention is also drawn to the fact that (I.2.7) should be corrected to read

$$p = \frac{c}{2} \cdot \alpha^2 \cdot \frac{2H_0D(e^{aL} - 1) - (H_L^2 - H_0^2)}{D^2(e^{aL} - 1 - aL)} \quad (23)$$

Note that the factor p as used in this formula signifies the rate of surface applied recharge and that the factor ϵ in the denominator is, therefore, lacking. Reference is made to the original article for an explanation of the symbols used. In the derivation of (I.2.7) the author erroneously associates the complementary function of the differential equation (8a) (the term z_1^2 of (I.2.3); that is, (I.1.3)) with a different value of D ($= D_0$ in Werner's notation) from the one used for the particular integral ($= D_m$). Although the complete solution is arrived at in a stepwise fashion, it is essentially a single solution for one (steady state) problem. There is no formal justification for separating any phases of the complete solution.

In deriving (8), Werner assumed that the variable z in (6) may be replaced by D, a weighted mean depth of the ground-water stream. In actual computations D is not known and a reasonable value must be chosen through some trials. If we make such trial computations with (II.2.6) for $p = 1.4 \times 10^{-4}$ m/day and for $D = 7.5$, 9, 10, 12, and 13 m, otherwise using the values given by Werner for his third example, we find that $z = 14.2$, 14.0, 14.0, 13.8, and 13.8 m, respectively. For $\alpha = 0$ we find from (II.2.7) that $z = 14.2$ m. It is observed that in this particular problem z (at $x = 0$) changes little even though D varies over a relatively wide range. *Dumm* [1954] gives a more detailed discussion of this aspect for formulas similar to those derived in the paper under discussion.

Formula (I.4.10) was derived earlier by *Jacob* [1943, 1944] for a water-table aquifer with large saturated thickness and was used to correlate ground-water levels with precipitation on Long Island, New York. There exists a special relationship between (6) of *Jacob* [1943] and (2) of *Dumm* [1954] (subsequently referred to as formula six and formula two, respectively) as evidenced by the following derivation. Let the rate of replenishment in formula six be r/t, where r is the amount of recharge during the interval t. From this slightly modified equation we immediately obtain the Fourier series of formula two for $t \rightarrow 0$ by applying l'Hopital's rule of limits. It thus follows that formula two is a special case of the problem treated by Werner and Jacob. Formula six may be said to describe the behavior of the water table in response to a 'step function' while formula two gives the fluctuation of the water table in response to an 'impulse,' that is, instantaneous recharge. It is beyond the scope of the present discussion to describe how these results may be used to analyze the behavior of the water table in response to consecutive recharges from repeated irrigations.

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P. Wilh. Werner (Vattenbyggnadsbyran, 29, Humlegardsgatan, Stockholm 5, Sweden; Author's closure)—The writer expresses his appreciation of Maasland's interest in the paper, as manifested through his general line of thought. However, in his discussion Maasland seems to misunderstand the use of the symbol p in the paper. In the writer's opinion the matter is very simple. If, for a moment, we define the applied surface recharge with p_s, we have the simple relation

$$p = p_s/\epsilon$$

Introducing this value, all formulas of the paper are still valid, and may be used without restriction also for p_s.

This also applies when transforming (1) in the paper to (22), provided that the latter formula is corrected so that the last terms in its left-hand member reads $c\alpha/\epsilon \cdot \partial z/\partial x$ instead of $\alpha/\epsilon \cdot \partial z/\partial x$; note that the same error also appears in Maasland's Eq. (21).

In his numerical computations of the weighted mean depth D, Maasland assumes the value $p_e = 1.4 \times 10^{-4}$ m/day. However, as far as the writer is aware, the calculations refer to the value $p_e = 1.4 \times 10^{-3}$ m/day.

With reference to the last sentences in Maasland's discussion, it is worth noting that some of the formulas given in the paper give the clue to investigating the effect of consecutive recharges from repeated irrigations. This is also mentioned in the paper.

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Reviews and Abstracts

ELIE CARAFOLI, *High-speed aerodynamics*, Pergamon Press, 710 pp., 1956, $15.00.

Carafoli's book is the English translation of the Roumanian volume Aerodinamica Vitezelor Mari. From his own work and that of others, he has attempted to provide the reader with a mathematical treatment of all aerodynamic problems which involve the compressible flow of air up to hypersonic speeds. Thus, the problems of subsonic wind tunnels, wings, and bodies are treated first, followed by similar treatments of the transonic and supersonic regimes. In 700 pages it is obviously impossible for him to go into great detail on any one subject with the result that the book abounds with mathematics and relatively little written text. The text is surprisingly clear and easy to follow.

Experimental data are used to a limited degree to illustrate various aspects of theory or physical phenomena. The subordination of experimental verification of theory requires the reader to be careful in accepting the material presented. Thus, while the findings are carefully qualified, the reader must extend his knowledge of a particular item by reference to other works.

The greatest value of this book appears to be as a reference for aerodynamicists, since most modern theories are collected in a single volume. It would be a convenient source of information on the theories of compressible flow for personnel in other fields who, on occasion, need aerodynamic theory in their work.

PHILIP DONELY

JOHN H. YOE AND HENRY J. KOCH, JR. (ed.) *Trace Analysis*, John Wiley and sons, xiii; 672 pp., 1957, $12.00.

This volume is the report of a Symposium on Trace Elements, sponsored by the Rockefeller Foundation and the Sloan-Kettering Institute, and held at the New York Academy of Medicine, November 2–4, 1955. It contains 24 chapters, with discussion, by authorities in each field, with emphasis on the theoretical background, sensitivity and applicability of each method, and practical uses. Although the major emphasis in the book is on biological applications, some of the sections include mention of geochemical work, and many of the methods are directly applicable to geochemical problems. Among these are *Chromatography* by H. H. Strain, *Ion exchange* by K. A. Kraus, *Spot tests* by Fritz Feigl and P. A. West, *Colorimetry* by M. G. Mellon, *Fluorometry* by C. E. White, *Flame spectrometry* by B. L. Valee, *Emission spectrochemical analysis* by L. W. Strock and R. L. Mitchell, *Mass spectroscopy* by M. G. Inghram, *X-ray spectroscopy* by Theodore Hall, and *Neutron-activation analysis* by A. A. Smales.

The book is highly recommended to anyone concerned with trace-element analysis, including both those making such analyses and those who wish to know their possibilities and limitations. Special praise is due the publishers for the fine job of printing and reproduction.

MICHAEL FLEISCHER

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Notes and Personalia

Notes

VISITING LECTURER SOUGHT IN GEOPHYSICS—For the interval of March 15 to June 15, 1959, the University of Minnesota is in search of a recognized authority on most any phase of the broad aspects of geophysics, including exploration, preferably one who has an interest in geology or physics, or both. There is a substantial honorarium. Recommendations are solicited. Suggestions and recommendations should be sent to Harold M. Mooney, Chairman of the Department of Geophysics, University of Minnesota, Minneapolis 14, Minnesota.

TWENTY-FIRST INTERNATIONAL GEOLOGICAL CONGRESS—The Twenty-first International Congress will be held August 15–25, 1960, with headquarters in the building of the Mineralogical-Geological Museum of the University of Copenhagen in Denmark. The first circular is now available in the United States and Canada from the American Geological Institute, 2101 Constitution Avenue, N. W., Washington 25, D. C., and those in other countries should apply to their respective national offices or to the Organizing Committee at the Mineralogical Museum noted above. The American Geological Institute notes that all persons requesting the first circular will be placed on the mailing list to receive travel literature and other pertinent information.

POSTDOCTORAL FELLOWSHIPS OF THE NATIONAL SCIENCE FOUNDATION—The National Science Foundation has announced that these fellowships will be awarded annually in December as previously. Applications must be filed by October 15, 1958. Inquiries should be addressed to the Division of Scientific Personnel and Education, National Science Foundation, Washington 25, D. C.

FOREIGN FIELD RESEARCH PROGRAM—The National Academy of Sciences-National Research Council announces the availability of funds to support graduate level research work in areas outside the English-speaking areas of North America, not only for geographers but also for geomorphologists, climatologists, ecologists, pedologists, etc. Further information may be secured by writing to the Foreign Field Research Program, Division of Earth Sciences, 2101 Constitution Avenue, N. W., Washington 25, D. C.

FULBRIGHT AWARDS IN EUROPE, ASIA, AND AFRICA—Announcement has been made of university lecturships and advance research opportunities under the Fulbright Act in various countries of the Eastern Hemisphere. Interested persons should write to the Conference Board of the Associated Research Councils, Committee on International Exchange of Persons, 2101 Constitution Avenue, Washington 25, D. C. The closing date for applications is October 1.

COST OF RESEARCH AND DEVELOPMENT—A recent survey by the Bureau of Labor Statistics made for the National Science Foundation showed that the total expended on research and development in industry in 1956 was $6.5 billion, an increase of $2.8 billion since 1953. The Federal Government's expanding research and development program has contributed substantially to this, increasing 37 per cent in 1953 and to almost 50 per cent in 1956. Copies of this report entitled Reviews of Data on Research and Development, No. 10, May 1958, may be secured by writing to the National Science Foundation, Washington 25, D. C.

NEW MAP OF SAUDI ARABIA—A new map of Saudi Arabia sponsored by a number of groups has been published by the U. S. Geological Survey. The scale of the map is 1:2,000,000 on a sheet 48 x 55 inches and may be secured from the U. S. Geological Survey, Washington, D. C., at a price of $1.50. Copies may also be secured of the Arabic version from the Directorate General of Petroleum and Mineral Affairs, Jiddah and Ad Dammam, Saudi Arabia.

SCIENTIFIC PROCEEDINGS OF THE INTERNATIONAL ASSOCIATION OF METEOROLOGY—The Proceedings of the Tenth General Assembly held in Rome in September 1954 are available directly from the Association (R. C. Sutcliffe, Secretary, I.A.M.A.P., Meteorological Office, Victory House, Kingsway, London, W.C.2, England) at a price of 60 shillings. This volume contains some 100 scientific papers by authorities in various fields. Its former price was 80 shillings.

FALL MEETING OF URSI—The fall meeting of the

U. S. National Committee of the International Scientific Radio Union will be held at University Park, Pennsylvania, October 20–22, 1958. Interested persons should get into touch with the National Committee Office in care of the National Academy of Sciences-National Research Council, 2101 Constitution Avenue, N. W., Washington 25, D. C.

HEAT TRANSFER AND FLUID MECHANICS INSTITUTE—This Institute convened at the University of California at Berkeley, June 19–21, 1958. Its purposes are "to promote the preparation of, and provide facilities for the presentation of scientific and technical work of a fundamental nature in thermodynamics, fluid mechanics, and related fields of scientific endeavor." Sponsors of the Institute are California Institute of Technology, Stanford University, University of California, University of Santa Clara, University of Southern California, American Institute of Chemical Engineers, American Rocket Society, American Society of Mechanical Engineers, American Society of Refrigerating Engineers, and the Institute of the Aeronautical Sciences. The papers presented at the Institute were published in advance of the meeting by the Stanford University Press in a volume containing 264 pages.

EXTENSION OF HURRICANE OBSERVATION NETWORK—The U. S. Weather Bureau has announced the establishment of more than 100 new cooperative reporting substations in the hurricane-observing network, ranging from Eastport, Maine, to Brownsville, Texas. The cooperative hurricane stations are manned by unpaid volunteers and serve to supplement the full-time Weather Bureau stations already established. Each of the new stations has been equipped with specially designed wind speed and direction indicators, a barometer, and a rain gage, and ordinarily will make one set of observations each day but will report more frequently whenever a hurricane threatens.

Personalia

DETLEV W. BRONK, President of the National Academy of Sciences and of the Rockefeller Institute for Medical Research, has been renominated by President Eisenhower as a member of the National Science Board. He is now serving as Chairman of the Board.

CHARLES E. CARVER, JR., Research Associate at Woods Hole Oceanographic Institution, has accepted appointment as Associate Professor of Civil Engineering at the University of Massachusetts at Amherst and will undertake his new duties as of September 1, 1958.

VEN TE CHOW, Professor of Hydraulic Engineering, University of Illinois, is making a consultation and lecture tour around the world covering points in England, France, Belgium, Austria, Turkey, India, Thailand, Japan, and the Hawaiian Islands.

ROBERT E. DILS, Associate Professor of Water Resources at the University of Michigan, has taken up duties as Head of the Cooperative Watershed Management Unit established in the College of Forestry and Range Management at Colorado State University.

EARL G. DROESSLER of the National Science Foundation has recently been awarded an honorary Doctor of Science degree by Loras College, his Alma Mater. He has only recently left his duties in the Office of Science of the Department of Defense to serve as Program Director for Atmospheric Science in the National Science Foundation. This a newly established position resulting from the recommendations of the President's Committee on Weather Control and the Committee on Meteorology of the National Academy of Sciences-National Research Council.

ARTHUR W. HARRINGTON, District Engineer with the Water Resources Branch of the U. S. Geological Survey, with headquarters at Albany, New York, retired recently after more than 42 years of service.

JOHN B. HERSEY, jointly with Mrs. Hersey of the Woods Hole Oceanographic Institution, was recently awarded the John Fleming Medal of the American Institute of Geonomy and Natural Resources "for outstanding accomplishment in science and human welfare".

MYRON G. H. LIGDA, formerly Associate Professor of Meteorology at Texas A and M College, has taken up duties as Head of Radar Aerophysics Group of the Stanford Research Institute.

G. J. F. MACDONALD of the Department of Geology and Geophysics at the Massachusetts Institute of Technology has accepted an appointment as Professor of Geophysics at the Institute of Geophysics, University of California at Los Angeles.

HUGH ODISHAW, Director of the U. S. National Committee for the International Geophysical Year, has been awarded an honorary doctor's degree by Carleton College.

TROY L. PEWE Staff Geologist of the Alaskan Branch of the U. S. Geological Survey, and Associate Professor of Geology at the University of Alaska, has recently returned after spending a season in Antarctica in charge of a glacial party in the McMurdo Sound area making observations on Quaternary glacial chronology, permafrost, and polygonal ground.

DONALD A. RICE, Chief of the Gravity and Astronomy Branch of the Geodesy Division, U. S. Coast and Geodetic Survey, has been awarded the Colbert Medal for his "important contributions to the Department of Defense in the fields of gravimetric and topographic-isostatic reductions of the deflection of the vertical and of gravity."

PAUL B. SEARS, Chairman of the Conservation Program, Yale University, has been nominated by President Eisenhower as a member of the National Science Board. The nomination is now awaiting action by the Senate.

PAUL A. SIPLE, Biogeographer of the Research and Development Division, Office of Chief of Staff of the War Department, was recently awarded an honorary doctorate by Boston University.

ROBERT B. SOSMAN, Professor of Ceramics at Rutgers University, has received the Trinks Award, the highest honor of the industrial heating industry, for his pioneering research work in silica, steel-making refractories, and pyrometry.

ATHELSTAN SPILHAUS, Dean of the Institute of Technology, University of Minnesota, has resigned as a member from the United States of the UNESCO Executive Board.

Joseph E. Upson, Research Geologist with the U. S. Geological Survey, was recently given one of the nine Rockefeller Public Service Awards for his work in Holland with Dutch hydrologists on the methods of management of fresh-water resources along the coast.

Harold R. Wanless, Professor of Geology at the University of Illinois, has received a Fulbright Research Fellowship for nine months of work in Australia where he will study coal measures, carboniferous rocks, and ancient glaciation. He will also lecture at the University of Sydney.

Townsend Cromwell, Research Associate of the Scripps Institution of Oceanography and Senior Scientist with the Inter-American Tropical Tuna Commission in San Diego, was killed in an airplane crash on June 2 enroute to Acapulco to join the Scot Expedition aboard the research vessel *Spencer F. Baird.* He was born in Boston, Massachusetts, in 1922. He took his baccalaureate degree at the University of California in Los Angeles in 1947 after serving in the armed forces during the war period. He took his master's degree from the University of California at La Jolla in oceanography in 1949. He became a member of AGU in 1956.

Victor H. Jones of the Sedimentation Section of the Soil Conservation Service, Beltsville, Maryland, died March 6, 1958, at the age of 52. He was born in Sparta, Minnesota, took his baccalaureate degree from the University of Minnesota in 1926, his master's degree from the University of Iowa in 1928, and his doctorate from Iowa in 1933. During his graduate years he was Research Assistant at the University of Iowa and spent summers as Assistant Geologist with the Illinois State Geological Survey. In 1931 he took up duties as Assistant Professor of Geology at North Dakota State College and in 1934 and 1935 he was a Field Geologist with the Iowa Geological Survey. Since 1935 he had been associated with the Soil Conservation Service, chiefly on sedimentation studies. He became a member of the American Geophysical Union in 1943.

Union, Section, and Committee Activities

Minutes of Executive Committee Meeting, American Geophysical Union First Session, May 4, 1958

The meeting was called to order at 14h 00m in the Board Room of the National Academy of Sciences—National Research Council Building, 2101 Constitution Avenue, Washington, D. C., by Vice President Lloyd V. Berkner, who reported that President Maurice Ewing is recuperating from an operation at the Johns Hopkins University Hospital and had asked him to preside.

Present—P. H. Abelson, L. H. Adams, L. T. Aldrich, Werner A. Baum, Hugo Benioff, L. V. Berkner, Harry F. Blaney, Walter H. Bucher, J. J. Capello, Frank L. Culley, Earl G. Droessler, N. C. Gerson, H. H. Hess, Albert J Hoskinson, B. F. Howell, Jr., W. C. Jacobs, H. R. Joesting, J. W. Joyce, Joseph Kaplan, W. C. Krumbein, W. D. Lambert, H. E. Landsberg, Walter B. Langbein, John Lyman, Thomas F. Malone, J. H. Nelson, John A. O'Keefe, James A. Peoples, Jr., Charles Pierce, John C. Reed, A. N. Sayre, M. O. Schmidt, A. C. Simonpietri, Waldo E. Smith, Charles A. Whitten, and R. N. Wilson.

Approval of minutes—The minutes of the Executive Committee meeting held on October 25, 1957, published in the February 1958 issue of the *Transactions* (pp. 145–156), were approved.

General Secretary's Report

The last report of the General Secretary is recorded in the minutes of the Executive Committee meeting of October 25, 1957, published in the February 1958 issue of the *Transactions* (pp. 145–148).

Publications—The following issues of the *Transactions* have been printed and distributed since our last meeting:

- October 1957—188 numbered pages of text plus 20 unnumbered pages including 11½ pages of paid advertising; edition of 6200
- December 1957—205 numbered pages of text plus 15 unnumbered pages including 10 pages of paid advertising; edition of 6200
- February 1958—194 numbered pages of text plus 14 unnumbered pages including 8 pages of paid advertising; edition of 6400
- April 1958—190 numbered pages of text plus 18 unnumbered pages including 9 pages of paid advertising; edition of 6400

Through this interval we have continued to publish the *IGY Bulletin* in the closing pages of each issue, and the text proper aside from the *Bulletin* has been somewhat larger than we had anticipated. While the cost of printing the *IGY Bulletin* material is reimbursed by the U. S. National Committee for IGY, the larger number of regular text pages plus the increase in printing costs effective this year will cause us to exceed our current printing budget by a substantial amount, and recommendations will be made later concerning this matter.

The President's committee to study the problem of joining the *Transactions* with the *Journal of Geophysical Research* has pursued its work actively and will, I believe, make an important recommendation at this meeting for your consideration.

Advertising in the *Transactions* hit a peak in the August 1957 issue. On that occasion Chairman Gerson's Committee on Advertising made a special effort to secure as much additional advertising as possible, with the result that this issue contained 17¾ pages of paid advertising. The rates were increased beginning with that issue, but the one-shot ads for the August issue could not be counted on. Howland and Howland took over as our advertising representatives starting with the October issue at the new rate, and the total declined to a low of eight pages in February. The number of pages is nine in the April issue, and we are hopeful that this marks the beginning of a substantial increase. Anything that any of you can do (1) to secure advertising direct or (2) give us names of key persons in organizations that should advertise will be greatly appreciated.

Permission was given to the Microcard Foundation to manufacture and sell microcards of our *Transactions*. The original grant carried no provision for royalty, but the renewal made at the beginning of 1957 called for a ten per cent royalty, and the AGU has received a payment of about $123. In the future we should receive not only royalties from this source but also on the sales of the reprinted *Transactions* being undertaken by the Johnson Reprint Corporation.

The Editorial and Publication Committee has met regularly at bimonthly intervals to consider the many problems of the *Transactions*, including means for progressive improvement.

Plans have been completed for the publication of Geophysical Monograph No. 2 on the symposium on the IGY which was held in Washington at the time of the opening of the IGY last July. Some 30 papers will appear in this monograph, and it will run to about 200 pages. This will be handled on the same basis as Geophysical Monograph No. 1. We shall sell copies with the expectation of recovering the cost. But to the extent that this is not successful, the U. S. National Committee will purchase additional copies.

Application has been made to the National Science Foundation for $4000 to cover the cost of Geophysical Monograph No. 3.

The Russian translation project has been moving along exceedingly slowly, although Nos. 1 and 2 of *Izvestiia* (Geophysics Series) have now been released. This leaves ten numbers yet to be published. The quality of the translations of the first two numbers has been only fair and efforts are being made to improve the succeeding translations. The Special Board on the Russian Translation Project consisting of Perry Byerly (Chairman), Werner A. Baum, Walter B. Langbein, John Lyman, F. W. Reichelderfer, A. E. Scheidegger, Waldo E. Smith, and Victor Vacquier met on February 21 to consider these problems and recommended that the abstract journal based on translated abstracts from the Russian be discontinued because of the poor quality of the abstracts and their translations. We are now attempting to work out means to close up that phase of the project, both with Pergamon Press and with the National Science Foundation. It will involve setting up the project on a new basis, and negotiations are proceeding slowly. In this connection, representation is being made to the National Science Foundation for an appropriate overhead (preferably 15 pct) as recommended by the Executive Committee at its meeting on October 25, 1957.

Membership—Membership data as of April 21, 1958, are:

Membership as of October 16, 1957	5021	
Reactivated	6	
New Members, October 16, 1957 to April 21, 1958, including 69 applications now being processed toward membership	274	5301
Resigned	97	
Inactive	5	
Dropped 27; tentatively dropped 148 (see below)	175	
Deceased (reported since October 16, 1957)	16	293
Total April 21, 1958		5008

Dues unpaid—As of April 21, 1958, the following dues were unpaid:

Owe for 1958	605
Owe for part of 1958	12
Owe for 1957	181
Owe for part of 1957 and all of 1958	8

In addition, there are 148 persons who have not paid dues in full for 1956. According to the Statutes and By-Laws, these are hereby recommended to the Executive Committee to be dropped from membership, but with the usual added recommendation that one more effort be made to return them to active membership.

Deaths—The following 16 deaths have been reported to the office of the Union since our last meeting: Hyseyin Pektas, June 11, 1957; David W. Mann, July 2, 1957; Reginald A. Daly, September 19, 1957; E. Raymond Shepard, October 17, 1957; John C. Jensen, October 19, 1957; Richard C. Hubley, October 28, 1957; Robert T. Knapp, November 7, 1957; Howard E. Tatel, November 15, 1957; Henry C. Cortes, December 6, 1957; Elbridge C. Jacobs, December 12, 1957; Roy W. Goranson, December 25, 1957; Charles F. Brooks, January 8, 1958; Edmund Schulman, January 8, 1958; Henryk Arctowski, February 20, 1958; Peter H. Ottosen, March 31, 1958; Willis I. Milham, March 23, 1958.

Finances—Below is a brief statement of our assets as of April 1, 1958, in comparison with the last two years.

	Apr. 1, 1958	Apr. 1, 1957	Apr. 1, 1956
Cash balance	$39,402*	$32,732	$30,424
Permanent Fund	14,589[a]	13,741[a]	12,834[a]
Emergency Fund	1,000	1,000	1,000
T. M. and E. Award Fund	1,311	1,268	985
Russian Translation Fund	32,477	—	—
Totals	$88,779	$48,741	$45,243

* February issue of 1958 not yet paid, reducing this by $5500 to about $34,000.

[a] Does not include accumulated interest on $2368 of U. S. Savings Bonds. The total at this time of the year tends to give the wrong impression because most of our income for the year has been received and most of our expenditures are still ahead.

As noted above, our printing costs have gone up sharply this year, and it is now estimated that the

$24,000 budgeted a year ago will fall short of meeting requirements by about $7000.

It appears that under general office expenses most of the items are adequate, but salaries and social security appear now to be running about $2000 above the budget ($17,000 to $19,000), stationery and supplies about $500 ($1500 to $2000), and postage and communications about $200 ($1500 to $1700). The General Secretary has recommended to the Budget Committee that appropriate recommendations be made to you to cover these increases. Also our annual meetings cost somewhat more than the budget allowance, and an increase of $500 is indicated. Reprints likewise are apparently running over the budget amount, but this simply means that the income will also run over the budget amount and an increase from $2200 to $2500 in the cost means an increase of about twice that in receipts. Only a small part of the $500 set aside for equipment has been used. Sometime soon it will be necessary for us to replace our addressing equipment which will necessitate an outlay of $1000 or more, so we are attempting to hold the item down in anticipation of this contemplated expenditure. We will have a more detailed report on the current budget from the Budget Committee.

It is obvious that if we continue the publication of the *Transactions* on the present scale, an increase in dues of at least $1.00 and possibly $2.00 per year will be necessary beginning in 1959.

The financial statement for the year ending June 30 will be submitted to the Audit Committee as promptly as possible after the close of the fiscal year.

Office staff and jobs—It was not possible for Antioch College to supply us with a student during the current interval, and it is thus necessary to employ a fourth full-time staff member. The other full-time members are James J. Capello, Ethel G. Sanders, and Waldo E. Smith, Executive Secretary. In addition, Glenda Quinn Olmstead and Barry Modlin are continuing on a part-time basis as reported last October. We are in search of a clerk-typist to fill the fourth job.

Quarters—There has been no change in our present arrangements, and we continue to occupy five rooms in the building of the American Association for the Advancement of Science.

International matters—The Committee on International Participation met in New York on January 10. Chairman Joyce will make an extended report relative to the work of this Committee and the urgent need for a substantial revamping of the U. S. National Committee to make it a more effective instrument for carrying out its functions in AGU, the NAS-NRC, and the International Union of Geodesy and Geophysics. The recommended changes will involve changes in the governing board of AGU, that is, this Executive Committee. Changes have been urged upon us by the National Academy, and the need for these was underscored by the meeting in Toronto last September.

Meetings—The Pacific Northwest Regional Group held its meeting in Pullman, Washington, October 29–30, 1957. This was attended by the Executive Secretary, who subsequently proceeded to Seattle to clarify matters relating to the International Association of Oceanography in accordance with the instructions of the Executive Committee. The meeting in Pullman was a decided success and was attended by about 125.

The conference on Atmospheric Chemistry of the Compounds of Chlorine and Sulphur was held in Cincinnati, November 4–6, 1957, in cooperation with the U. S. Public Health Service and under the direction of Chairman James P. Lodge, Jr., of the Committee on Atmospheric Chemistry of our Section of Meteorology. The National Science Foundation made a grant of $4000 available chiefly to cover the cost of travel of foreign participants. The meeting was an outstanding success, and steps are now being taken to secure a grant of about $4000 more from the NSF to underwrite the publication of the results as Geophysical Monograph No. 3. To the extent that sales exceed costs, the fund, if received, will be returned to the NSF.

The AGU co-sponsored a session on December 30 on "Man and his environment, Part 1, Outdoor environment" at the AAAS meeting held in Indianapolis, December 26–30, 1957. At the coming meeting of AAAS, the Section on Agriculture has asked that we co-sponsor their symposium on water and agriculture. This invitation has been accepted.

The annual meeting of the Pacific Southwest Regional Group was held in Pasadena, February 6–7, 1958, with about 200 persons in attendance. The General Secretary had planned to attend this meeting, but was unable to do so, and none of the AGU officers was able to attend.

Plans for our annual meeting May 5–8, 1958, are complete, and the program is in your hands. It was decided to hold one session open (Tuesday afternoon) for late developments in IGY. N. C. Gerson, as Chairman of the Committee on AGU-IGY Relations, has arranged an interesting program for this session.

The Committee on Cloud Physics of the Section of Meteorology is hoping to hold another one of its successful conferences within the next year. It had hoped to do this in September 1958, but the time is now getting short. Approval has been received from the National Academy to apply for a grant to the National Science Foundation for $20,000 to hold the conference and another $10,000 to publish the results as a geophysical monograph.

Statutes and By-Laws—The ballot concerning certain changes in the Statutes was mailed out in December with the dues notices, and the ballots were tallied by the Committee of Tellers under the chairmanship of J. H. Nelson. The results of this ballot overwhelmingly favored all of the changes. Having also been approved by the National Academy, they are now in effect. The results appeared in the April 1958 issue of the *Transactions* (page 351).

American Geological Institute—Henry R. Joesting completed his second term as one of our representatives on the Board of Directors and James R. Balsley, Jr. was appointed in his place. Our representatives are now James R. Balsley, Jr., and Walter H. Bucher.

Nominating Committees—All of the Sections have now activated Nominating Committees in order to bring in nominees for the Section officers, and the Chairman of the Union's Committee on Nominations (L. H. Adams) has activated his Committee. We anticipate that nominations will be completed by late summer so that the meeting of the Executive Committee relative to these and other matters may be held in late September or early October 1958. One Section (Hydrology) has already reported its official nominees.

Miscellaneous—An overall meeting on abstracting and indexing in science was called by *Biological Abstracts* and held in Philadelphia, January 29-31, 1958, under the sponsorship of the National Science Foundation. This was a call to see what could be done with regard to science on a world-wide basis, and much enthusiasm was engendered for a voluntary federation to accomplish this job and to be sure that the entire field of science is adequately covered. It was pointed out that some 500,000 titles are covered currently by existing abstract journals, but the total is probably on the order of two million and to cover these adequately, including their indexing, will probably cost on the order of twenty million dollars a year. The meeting was attended by the Executive Secretary. In geophysics it was estimated that some 12,000 items a year should be covered, including those now covered by *Meteorological Abstracts* which total about 3000. The overall cost would probably be on the order of $120,000 to $130,000 per year. The AGU should indicate its willingness to take the lead in this and perhaps become a member of the newly organized National Federation of Scientific Abstracting and Indexing Services. In the absence of the President and the Vice President, the opportune meeting of the Board on the Russian Translation Project on February 21 and the fact that this project is concerned with the matter of Russian abstracts, Chairman Byerly of that Board appointed Werner A. Baum as Chairman of a subcommittee to study the problem for and on behalf of AGU.

The General Secretary attended the meeting of the Executive Committee, Office of Critical Tables, National Academy of Sciences, on February 3, 1958. We have recently received an invitation to name a representative on the Advisory Board of the Office of Critical Tables. President Ewing has requested Francis Birch to serve, but he is already on the Board. Suggestions are invited.

AGU forwarded its Annual Report for 1956-57 to the NAS-NRC in the late autumn of 1957.

The American Association for the Advancement of Science held a Parliament of Science at Washington, March 15-17, 1958, to consider the problem of education in science, which was attended by a representative group of over 100 American scientists and public leaders, including over 60 accredited observers. A number of AGU members took part in these deliberations, and a report of the conference was published in *Science*, April 18, 1958.

The AGU has received invitations to send representatives to a number of meetings during the last few months, among these being the Symposium on Natural Resources of Cuba, February 3-14 (Dr. Robert H. Randall and Dr. Andre C. Simonpietri were named as our representatives), and the meeting of the Pan American Institute of Geography and History held in Havana, February 12-22 (the following were designated: G. Medina, Chairman; Andre C. Simonpietri, Secretary; L. P. Disney, Albert J Hoskinson, David L. Mills, Leonard M. Murphy, George D. Whitmore, and Charles A. Whitten). Earl G. Droessler was designated as representative at the inauguration ceremony for the new Rector of Catholic University on April 16.

A. NELSON SAYRE,
General Secretary

Action on the General Secretary's report—The report was accepted.

Actions on matters relating to the General Secretary's report—The recommendation that the persons who have not paid dues in full for 1956 be dropped from membership after making one more effort to return them to active membership was accepted.

There was extensive discussion of the suggestion that AGU become a member of the newly organized National Federation of Scientific Abstracting and Indexing Service to be of assistance in implementing the abstracting and indexing of geophysical items. A motion was made and approved that AGU adhere to the National Federation of Scientific Abstracting and Indexing Service without financial commitment, and that $500 be appropriated from present funds for the Russian Translation Project to the new Federation if the National Science Foundation will approve this use of these funds. It was noted that a representative is to be designated. To study this problem, an *ad hoc* Committee consisting of John Lyman (Chairman), Werner A. Baum, J. W. Joyce, John C. Reed, and possibly one more, was designated. A motion was approved that AGU go on record as favoring the objective of a complete geophysical abstract journal which may be subdivided into sections involving specified units, but that this should be done without financial encroachment upon the regular funds of the Union. The thought was expressed that having the abstract journal in sections (such as the *Bulletin Signaletique*) would permit individuals to get the sections for their particular field.

Report for the President—In the absence of the President, Vice President Berkner noted that President Ewing had a feeling of great urgency with regard to matters pending for action, which actions he believed are important to strengthen the Union greatly, and that it is essential that we take some chances in the effort to improve the state of geophysics in the United States. Accordingly, the order of the agenda was suspended, and it was agreed that we should first hear the report of the Committee on Budget which had considered the problem under the status quo and that following this there should be a report of the Special Committee on Publications with subsequent further consideration of the budget report.

Budget Committee—Chairman John C. Reed presented a report indicating a deficit for the fiscal year ending June 30, 1958, of about $8250 and pointing out the need for further increased income to have a balanced budget. The report of the Committee was accepted, this not involving approval, and the Executive Committee went into brief executive session with regard to certain aspects of the budget problem.

Special Committee on Publications—Chairman James A. Peoples, Jr., presented the report published as Appendix 1. This, in essence, proposes dividing the *Transactions* into two parts. One would be a purely scientific and technological journal to be issued monthly, containing initially about 100 pages of papers per month well balanced across the broad field of geophysics and to be called *Research in Geophysics* or some other appropriate name. The notes and personalia, Union activities, and other material of a limited- or transient-interest or semi-popular nature would be published presumably on a quarterly basis, continuing the name *Transactions*. This endeavor, according to the budget tentatively drawn up, would result in a deficit of $16,000 or $17,000 a year. Thus a grant, say, of $50,000 for the first three years would be needed to put these journals on a permanent footing. The plan would be effective January 1, 1959.

The problem was broadly discussed. It was felt that the monthly journal with facilities for expansion should do a great deal to meet the greatly increased needs of geophysics and perhaps double the advertising potential of the journal. The Vice President cited a recent experiment in writing letters to 20 friends in high positions in corporations outlining the advantages of advertising in the AGU publications and of taking out corporation membership, feeling that if this experiment is successful other members should be urged to do likewise. Budget Chairman Reed pointed out that the budget deficit of $8000 in prospect on the status quo basis indicates the need for increasing dues or tapping some other sources of income. Kaplan stated that he felt that the quarterly publication containing semi-popular material might well provide authentic material needed by high school teachers and science writers, and that we should perhaps use some other title such as *Bulletin of American Geophysicists* or *Geophysics This Month* or *Geophysics in the Modern World* and use a sub-title "Formerly *Transactions* of the AGU," with a similar provision for expansion in this material to meet the increasing needs and possibly ultimately publishing it on a monthly basis. The amount of money that the National Science Foundation is spending to improve science teaching would justify serious effort on our part to help to meet this demand and somehow reach the professionally-minded teachers of science, although it was generally agreed that the primary responsibility of AGU is to publish a journal for professionals in geophysics that will be accorded world-wide respect. It was felt that a semi-popular publication should be handled as a separate or auxiliary project to the main project under consideration. It was noted that if the National Science Foundation chose to give support, they would prefer to subsidize a new journal, possibly including one that would publish IGY results.

The main effort will include the making of a serious personal effort to encourage those doing interesting work in geophysics to provide strong articles for this journal and improve its balance.

It is felt that a good case can be made for establishing a page charge levied against authors' institutions as suggested by Peoples' report (Appendix 1), but in no case would it be levied against the individual authors. This has worked out successfully for other journals. It was noted that the per-page charge probably would be quite essential to securing a grant from the National Science Foundation. It was also noted that the Controller General has ruled that page charges may be paid by Federal agencies.

A question was raised concerning the proposed payment to the editor of $500 per issue. The thought, expressed elsewhere, was repeated that we hope the editor would be a part-time individual (as someone put it, work half time for about one-quarter-time compensation) and that half of the amount would presumably be for secretarial assistance and the other half would be an honorarium.

It was pointed out that up through 1944, John A. Fleming as General Secretary acted in the capacity of editor-in-chief. While the Editorial and Publication Committee technique has been successful in raising the quality of the *Transactions* considerably in the interim period, there was a strong feeling that if a person of the right caliber can be secured, the editor-in-chief idea is perhaps preferable. It was felt that we should push hard to make the publications of AGU the top research journal in geophysics and that IGY results should provide a wealth of material for it.

A motion was made and approved adopting the report of the Special Committee on Publications (Appendix 1) from its beginning through the paragraph headed *Transactions* but not including Financial Matters, with instructions to the Committee to examine further the question of the title of the scientific journal as well as the modified *Transactions, AGU*.

A motion was made and approved adopting a page charge from authors' institutions in the United States and Canada which would entitle the accepters of this page charge to 100 reprints without further charge, this to go into effect with the new journal. It is understood that when an author's institution did not pay the page charge, this charge would be waived; however, the author would not receive free reprints. (Five voted in opposition.)

A motion was approved unanimously that the subscription rate should finally be set by the General Secretary, taking into consideration the recommendations of the Special Committee on Publications.

It was agreed that the successor to the *Transactions*, whether issued quarterly or more frequently and to include material of current interest, should be developed in accordance with the judgment of the officers with such assistance and advice as they may require.

It was further agreed that the Committee on Budget and the Special Committee on Publications should work together on the details of the plan approved to clarify the various questions raised concerning the financial matters in the report under Appendix 1, and that on the completion of the work of these two committees the budget for the fiscal year 1959 should be sent to the Executive Committee for mail ballot.

Reports of Standing Committees

Budget—A motion was passed approving the departures which the Committee recommended in its budget for the current year. This largely relates to the increases in cost (about $8000) in publication over that set forth in the budget published in the August 1957 issue of the *Transactions* (pp. 606–608).

A motion was made and approved that dues be raised from $8 to $10 for individual members beginning January 1, 1959, this being essential to meet budgetary requirements based on present operations. A motion was made and approved that students' dues ($3 per year) remain unchanged.

A motion was made and approved that the amount to be paid for life membership be increased from $150 (at present) to $200. (The By-Laws as amended to April 30, 1955, indicate that "Any Member or Associate, on payment of not less than $100 at any time, the amount to be fixed by the Executive Committee of the

Union, shall be relieved of further payment of dues." In 1956, the amount was placed at $150.)

Statutes and By-Laws—Walter B. Langbein, acting on behalf of Chairman K. Hilding Beij, made recommendations concerning the necessary changes in the Statutes and By-Laws to effectuate the changes in publications outlined in Appendix 1 and discussed above. The recommended changes, subject to modification with regard to titles of the publications, are set forth in Appendix 2. A motion of approval was passed. Notice is hereby given of the intent to change the By-Laws, and a ballot is to be sent out at an early date to the membership relating to the changes in the Statutes.

International Participation—Chairman J. W. Joyce submitted the report of the Committee given as Appendix 3 concerning the question of AGU representation at the International Union of Geodesy and Geophysics. Vice President Berkner noted that some changes are essential in order to make AGU more effective in discharging its responsibilities as the U. S. National Committee for the IUGG, that this matter should be discussed broadly among the members, and that any views developed should be conveyed to Chairman Joyce for inclusion in a further report for action by the Executive Committee at its fall meeting. He remarked that the relationship of AGU to IUGG is part and parcel of the life existence of AGU and must be retained, but there have been objections and criticisms from the National Academy of Sciences with respect to our present setup to meet these problems. Chairman Joyce noted that his Committee expects to work closely with the Committee on Statutes and By-Laws in recommending changes that seem to be appropriate.

It was further noted by Chairman Joyce that U. S. National Reports should be presented at each triennial meeting and that, if properly prepared, these should prove exceedingly useful to geophysics in the United States and would point out significant advances during successive three-year periods. We should attempt to eliminate dry factual presentations and encourage active and vital reports. A motion was made and approved that the National Report recommended by the Committee on International Participation be tried experimentally for the next General Assembly (four opposed).

Editorial and Publication—The General Secretary pointed out that this Committee has devoted a great deal of time and effort toward the improvement of the *Transactions*, editing papers, and excluding or condensing papers, and suggested that a resolution be passed commending the Committee on its zeal and high ability in carrying out its task. A motion was approved unanimously thanking the Editorial and Publication Committee for its continuing excellent work in the preparation of the *Transactions* and commending the Committee for the improvements made in format and contents which prepared the way for further expansion of the Union's publications.

In the absence of Chairman Perry Byerly of the Board on the Russian Translation Project, Werner A. Baum reported briefly concerning the activity of that Board, noting that it had met twice, February 21 and May 4, 1958. It is very much concerned with the slow development of the publication of the English edition of *Izvestiia* (Geophysics Series), noting that only Nos. 1 and 2 for 1957 have thus far been published and that the quality of the translations is not the best. He noted that the Board, at its meeting on May 4, met with I. R. Maxwell, President of Pergamon Press, and had received assurance that the translating difficulties have been largely overcome (there had been a turnover of 500 per cent in the translating personnel) and that Nos. 3, 4, and 5 should be issued in June 1958 and the other seven numbers by the end of August. The Board recommended that plans be laid for the continuance of the project for 1958, this to be with Pergamon Press only if a firm contract can be worked out bearing on problems of quality of translation and the appointment of suitable translation editors, a premium for early delivery and a penalty for late delivery, and the availability of funds from the National Science Foundation. If such negotiations cannot develop appropriately with Pergamon Press (assuming its commitments outlined above with respect to 1957 are fulfilled), then negotiations should be entered into with other companies with regard to *Izvestiia* for 1958. This recommendation was approved.

The Board also recommended that AGU seek funds from the National Science Foundation and, if available, negotiate a contract with some other translating publishers for the translation of *Trudy* of the Geophysical Institute of the Academy of Sciences of the USSR for 1958, using the same rules as suggested for *Izvestiia*. This was approved.

The Board also took cognizance of existing translations of books from the Russian and perhaps from other languages which have been made by United States agencies and which are not generally circulated at this time. It was also recommended by the Board that if we can assist the National Science Foundation in making these available through other than regular AGU funds, we should help to do so in every way possible. A motion was approved that the Executive Secretary, in consultation with the General Secretary and the Board, investigate this matter and initiate such a series if it appears appropriate and if support is available.

Nominations—Chairman L. H. Adams reported that initial steps have been taken looking towards a full report by late summer of 1958. All Sections were urged to have their reports complete by the middle of September, including biographies of candidates.

Meetings—Chairman P. H. Abelson reported that, in connection with arrangements for the Thirty-Ninth Annual Meeting, a few departures were made from past meetings, including a session devoted to IGY activity. He felt that the meetings next year should have a number of special sessions devoted to the IGY and its results. He noted that there has been favorable comment on plans for the dinner to be held in honor of the twentieth recipient of the William Bowie Medal, Prof. Johannes Theodoor Thijsse of The Netherlands, which will be attended by 45 or 50.

It was also noted that a regional meeting is to be held in Portland, Oregon, November 13–18, 1958, by the Pacific Northwest Regional Group at which Vice President Berkner plans to attend and address the group on some aspects of the IGY, a major theme of the meeting. The Pacific Southwest Regional Group will hold its meeting at Stanford University in January or February 1959.

The Committee on Cloud Physics of the Section of Meteorology held a highly successful conference in September 1955 and is laying plans for another conference to be held this fall, if possible. A request for funds has been made to the National Science Foundation to make this possible, including a reimbursable grant for publication of the conference proceedings as a monograph.

Membership—Chairman Earl G. Droessler reported briefly on developments since the meeting of October 25, 1957, and requested that members of the Executive Committee carefully look over the list of names of those about to be dropped for non-payment of dues and write to those whom they know to induce them to stay in the Union.

B. F. Howell, Jr., as Chairman of the Section on University Memberships, both students and faculty, reported briefly and noted that our student membership has grown substantially.

Reports of Special Committees

Relations of the AGU with the U. S. National Committee on IGY—Chairman N. C. Gerson reported that this Committee had organized a Symposium on Satellite Geophysical Studies for the afternoon of May 6 and stated that next year he would like to arrange three or four sessions in connection with the Annual Meeting relating to IGY activities. He noted further that he is maintaining touch with W. W. Atwood, Jr, relative to a joint venture whereby U. S. reports on IGY activities may be published through AGU, thinking that some of these at least might fit into our monograph series whereas others might be collections of contributions in various journals published in a given year.

Advertising—Chairman N. C. Gerson reported briefly, noting the recent effort by Vice President Berkner in writing 20 letters to friends in high positions in corporations relative to advertising. He noted further that the special effort of the Committee in connection with advertising in the August 1957 issue had been highly successful and that perhaps similar efforts should be made to increase advertising in the publications of the AGU on a permanent basis.

Geophysical and Geological Study of Continents—In the absence of Chairman George P. Woollard, it was noted that there was a brief report in hand relative to the work of this Committee. The report in full appeared in the June 1958 issue of the *Transactions*, pp. 492–496.

Resolutions—In the absence of Chairman John N. Adkins, a resolution was introduced and adopted expressing the Executive Committee's sympathy and hope for early recovery of President Ewing. The Executive Secretary was instructed to transmit this resolution by telegram.

Education—In the absence of Chairman John E. Nafe, it was noted that this Committee will meet on May 6.

Reports of Sections

Geodesy—President Milton O. Schmidt reported that there has been a broadening in the plan for annual programs by the Section of Geodesy that resulted in the holding of two sessions this year. John A. O'Keefe, Chairman of the Committee on Geodetic Applications of Artificial Satellites, reported briefly regarding two problems, namely, that the motion of the satellites is irregular partly because of tumbling and partly because of drag, and that celestial mechanics are now involved in geophysics. He noted that the first-order theory is not sufficient for the problems and that the second-order theory is very complex.

Seismology—Secretary James A. Peoples, Jr., reported that the Section is holding two sessions this year, both including excellent programs.

Meteorology—President H. E. Landsberg referred to the Conference on Atmospheric Chemistry of the Compounds of Chlorine and Sulphur held in Cincinnati in November 1957 in cooperation with the U. S. Public Health Service under the direction of Chairman James P. Lodge, Jr., of the Committee on Atmospheric Chemistry to the Section of Meteorology. It was noted that an application has been made to the National Science Foundation for a reimbursable grant of $3800 to underwrite the publication of the results of this conference as Geophysical Monograph No. 3. He further noted that the Committee on Cloud Physics of the Section of Meteorology is hoping to hold another conference within the next year. He mentioned that the AGU has been invited to be one of the cosponsors of a Symposium on Water and Agriculture to be held in connection with the AAAS meeting on December 29 and 30, 1958.

Geomagnetism and Aeronomy—The change in name of the Section was noted, and J. W. Joyce referred to the Symposium on Cosmic-Terrestrial Relationships to be held on May 6 as holding promise of being exceedingly outstanding.

National Research Council Reports

Physical Sciences—It was noted that L. T. Aldrich is now AGU representative in this Division.

Earth Sciences—Chairman H. H. Hess of the Division, who is our representative, reported on the successful conference on sea ice held by the Division in February 1958 and that a conference on drilling a hole through the crust of the Earth was held April 26, 1958. Frank Press has been designated to succeed Hess as AGU representative in the Division for the term starting July 1, 1958.

Affiliated Organizations

American Geological Institute—It was noted that a letter had been received from President J. V. Howell of the AGI indicating that something over 2400 members of AGU are not members of any other organization affiliated with AGI and suggesting that steps be taken that subscriptions for these persons may be covered by payment from AGU ($1200 suggested) or that these members be solicited for subscriptions and be dropped if they do not subscribe. The latter course seemed preferable to the Executive Committee as long as it did not drop these persons from the National Roster of Earth Scientists for which the AGI has responsibility. It was felt that most of these persons would not find it desirable to subscribe because the subject matter of geology covered by *GeoTimes* is largely outside of their interest. The matter was referred to the AGU representatives to make suitable recommendation to

President Ewing for reply to Howell. The further thought was expressed that AGU should take the responsibility for maintaining the roster of geophysicists and that perhaps there should be an affiliation of AGI with AGU.

American Association for the Advancement of Science—W. C. Krumbein, one of our two representatives on the Council of the AAAS, noted that our plans for the development of a program in connection with the AAAS meeting in Indianapolis last December did not develop because of the diversified character of that meeting.

Unfinished and New Business

Earl G. Droessler referred to a proposal made independently by Gerald J. Miatech and himself for the establishment of a suitable memorial in honor of the memory of James B. Macelwane, who at the time of his death was President of AGU. He suggested that AGU appoint an *ad hoc* committee to investigate this. With the consent of the Executive Committee, Droessler was asked to prepare a list of persons who might serve on such a committee and to make recommendations to the President as soon as possible.

With regard to the suggestion by S. F. Singer on the formation of a journal club in Washington to meet every two or three weeks, it was agreed that the AGU should encourage this endeavor, that it does not feel that as a national organization it can itself sponsor a purely local meeting, but that we will be glad to assist in offering moral support to the endeavor.

Attention was called to a proposal by A. J. Shneiderov that AGU sponsor a research project on paleomagnetism for support by the Office of Advanced Research of the Department of Defense. It was agreed that research activities, as such should not be undertaken by AGU and that this thought be conveyed to Shneiderov.

Reference was made to a proposal by a former member applying for readmission in the AGU on the basis that he be supplied with microcard copies of our publications instead of the publications themselves. A motion to authorize the Executive Secretary to put a note in the *Transactions* regarding this was lost.

Recess—The Executive Committee recessed at 18h 20m to resume its meeting immediately following the Business Meeting on May 7, 1958.

Second Session, May 7, 1958

The second session was called to order at 16h 45m by Vice President Berkner in the Auditorium of the National Academy of Sciences—National Research Council Building, 2101 Constitution Ave., N. W., Washington, D. C.

Present—Thirteen persons were present as follows: P. H. Abelson, L. H. Adams, Hugo Benioff, L. V. Berkner, J. J. Capello, Frank L. Culley, Earl G. Droessler, B. F. Howell, Jr., W. D. Lambert, J. A. Peoples, Jr., D. W. Pritchard, A. N. Sayre, and Waldo E. Smith.

L. H. Adams, Chairman of the Committee on Nominations, noted that under the rules adopted by the Executive Committee in the fall of 1946 preceding the first elections by mail ballot two nominees are required for each of the three elected officers of the Union and suggested that this requirement be made optional instead of mandatory. It was noted also that additional nominees may be added by petition of one per cent of the membership. Chairman Adams stated that it is sometimes advantageous to have two nominees for each office, but that from repeated experience on this Committee it is sometimes awkward and disadvantageous to find two nominees for each office. Secretary Howell of the Section of Tectonophysics noted that at the recent meeting of the Section it was agreed to eliminate the mandatory provision. Other Sections have likewise taken this step. After further discussion, a motion to refer this matter to the Committee on Statutes and By-Laws for study and recommendation to the Executive Committee for a vote by mail ballot was approved.

Adjournment—The meeting adjourned at 17h 05m.

A. Nelson Sayre, *General Secretary*
Waldo E. Smith, *Executive Secretary*

Appendix 1—Report of Special Committee on Publications*

Introduction—The International Geophysical Year has initiated a world-wide expansion of geophysical research, and recent developments clearly indicate that the present pace will continue or even expand with the official termination of the IGY. The geophysical journals as they exist today will not be able to publish all of the fine scientific reports which will surely result from this work.

The members of the American Geophysical Union need a larger and better balanced journal where the results of the geophysical investigations can be published promptly. Both the opportunity and the obligation are now apparent for the Union to assume its traditional role of bringing the various specialties together more effectively by establishing a scientific publication which covers all fields of geophysics including the expanding role of geophysics in space.

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* Since May 4, 1958, when this report was submitted to the Executive Committee, there have been substantial and favorable developments toward the modified scientific journal. M. A. Tuve, Director of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, has lent his enthusiastic support to the project and agreed to combine the *Journal of Geophysical Research* with our publication. Conferences with the National Science Foundation have indicated endorsement of our endeavor and raised the expectation that our application for a substantial grant will receive favorable consideration. Finally, two distinguished geophysical scientists have indicated their willingness to act as co-editors-in-chief of the modified journal. It is now planned that each monthly issue will contain some 200 pages of scientific material of high quality.—Ed.

It is, therefore, recommended that the Union establish a new scientific journal which will be called *Research in Geophysics* (name subject to change—Ed.). It will take over the publication of scientific reports from the *Transactions* (name subject to change—Ed.) and seek a better balance of papers in the various fields *by expansion*. It is intended that the publication will be one which every geophysicist will want to read and in which he will be proud to publish. International interest, support, and membership will be solicited.

Editorial policy—The entire publication will be devoted strictly to serious scientific matters, plus advertising. It will consist of: (1) original research reports; (2) authoritative and critical reviews of the developments within or between the various fields of geophysics; the reviews will be published on a basis of timeliness and availability; (3) a *Letters* department will provide for: (a) quick but brief publication of unusual results; (b) brief discussion of previous papers; and (4) abstracts of papers given at Union meetings.

All fields of geophysics are to be included, and those papers or reviews which provide an insight into the interrelationships of the different fields are especially desirable. Papers are to be accepted on a basis of scientific merit regardless of the source.

The Editor, assisted by his Advisory Board, will have the responsibility of maintaining a high standard for the papers published. Papers submitted will be judged critically but fairly by referees selected for their competence to judge in the field of each paper. Every reasonable effort will be made to help authors of papers to meet acceptable requirements. Final decision on publication will rest with the Editor.

Parallel with the selection and editing of papers, there must be active solicitation of good papers, especially in those fields which have not been well covered in the past. It is recommended that a special committee including foreign representatives be appointed to assist in this.

Research in geophysics will be published twelve times per year beginning with the January 1959 issue (Vol. 1, No. 1). The number of papers per issue will depend upon the availability of suitable material and finances. The objective for the first year is 100 pages of scientific material per issue, plus advertising.

Advertising will not only provide significant financial support to the journal, but it will enhance the attractiveness and usefulness of the publication. The members of the Union are asked to assist in an aggressive campaign to solicit more advertising.

Format—The general appearance of *Research in Geophysics* must be compatible with the editorial policy. It shall be well planned, modern and dignified, but without frills. The problems of the reader and of the librarian in cataloging, printing, binding, etc., shall be given due consideration. The details shall be left to the Editor and his Advisory Board to work out.

Editors—The major responsibility for *Research in Geophysics* will rest on the shoulders of the Editor. He will have final authority in accepting or rejecting papers and advertising, and it will be his responsibility to establish and maintain an outstanding publication. Since this task will require a great deal of time and will require secretarial assistance, the Editor will receive an appropriate honorarium.

The Advisory Board will consist of sufficient mem-

TABLE 1 – *One issue of Research in Geophysics (100 pages of text plus 20 plates of advertising and miscellaneous material, total 124 pages)*

Receipts	
Page charges 60 pages at $15	$900
Advertising 12 pages at $200 (average)	2400
Dues $\frac{1}{2} \times 3 \times 5000$	1250
Sales and subscriptions $\frac{1}{12} \times 16 \times 750$	875
	$5425
Expenditures	
Printing 7000 copies at $30 per page	$3600
Cover	50
Mailing	200
Office work	1200
Editor	500
Direct advertising	600
Reprints	400
	$6550

TABLE 2 – *One issue of Transactions of the American Geophysical Union (20 pages)*

Receipts	
Dues $\frac{1}{4} \times 1 \times 5000$	$1250
Sales and subscriptions $\frac{1}{4} \times 2 \times 750$	375
	$1625
Expenditures	
Printing 7000 copies at $30 per page	$600
Cover	25
Mailing	150
Office work and editing	300
	$1035

TABLE 3 – *Suggested annual Union budget covering Research in Geophysics (monthly) and Transactions (quarterly)*

Receipts	
Dues, 5000 members at $10	$50,000
24 corporation members at $100	2,400
Publications	
Sales and subscriptions 750×16	12,500
Advertising	28,800
Page charges	10,800
Interest	800
NRC Grant	400
	$105,200
Expenditures	
Research in Geophysics (12 × 6550)	$78,600
Transactions (4 × 1075)	4,300
General office	25,300
Expenses of meetings	1,500
Expenses of sections	100
Expenses of committees	100
Travel of officers	1,000
Directory reserve	1,500
Rent	3,700
President's fund	100
Contingencies	5,000
	$121,200

bers to represent the various specialties in geophysics. They will advise on general editorial policy and be responsible for refereeing the papers which are sent to them by the Editorial; they will be free to call on specialists to assist them in this work.

The Editor shall be appointed for an indefinite term by the Executive Committee. The Advisory Board shall be designated by the President in consultation with the Editor and the Executive Committee.

The Transactions—The *Transactions* shall be a regular periodical which contains reports of Union activities, notes and personalia, special announcements, and other material of a transitory or semi-popular nature. Initially it will be published on a quarterly basis.

Control of matter to be published in the *Transactions* shall rest in an Editorial and Publication Committee composed of one member from each Section designated by the Executive Committee of the Section. The General Secretary of the Union shall be *ex-officio* Chairman and the Executive Secretary shall be *ex-officio* Secretary. (Modified by approval of changes in Statutes and By-Laws; see Appendix 2—Ed.)

Financial matters (not adopted from this point onward—Ed.)—In order to finance *Research in Geophysics* and the *Transactions of the American Geophysical Union*, the following are recommended: (1) raise membership dues from $8.00 to $10.00 (Members would receive both publications); (2) solicit a fee of $15.00 per page from authors' institutions; no charge would be solicited for foreign contributions (except in Canada); no paper would be rejected solely because of inability to collect fee; (3) establish a subscription rate of $16.00 per year for both publications (in Table 1, taken as $14.00 per year for main journal, and in Table 2, $2.00 per year for the auxiliary journal); (4) solicit a grant of $50,000 to assist in the first three years of the publication; and (5) seek more advertising and more corporate memberships.

Tables 1 to 3 worked out by Waldo E. Smith and J. A. Peoples, Jr. are thought to be realistic estimates of the financial picture, if the above publication plan is adopted.

Table 3 indicates there may be a deficit of approximately $16,000 per year and it is for this reason that the securing of a grant is recommended.

J. A. Peoples, Jr., *Chairman*

Appendix 2—Suggested Amendments in Statutes and By-Laws to Implement the Peoples' Report

K. Hilding Beij, Chairman
Walter B. Langbein C. A. Whitten

Statutes

Article 1(b) To promote, coordinate, and facilitate the study of the various branches and interrelationships of geodesy and geophysics in the United States of America, its outlying territories, and the ocean; to provide for scientific discussion, publication, and dissemination of information relative to these fields through its publications.

Article 11: Publications—The official publications of the Union shall include the *Transactions of the American Geophysical Union*, *Research in Geophysics*, and the *Geophysical Monograph* series, published under the auspices of the National Academy of Sciences—National Research Council (titles subject to change—Ed.)

The *Transactions* shall be a regular periodical which contains the reports of Union activities, notes and personalia, special announcements, and other material of a transitory or semi-popular nature. Control of matter to be published in the *Transactions* shall rest in the Executive Secretary with the aid and counsel of the Secretaries of the several sections.

Research in Geophysics shall be a regular periodical which contains the scientific and technological papers and related departments. Control of matter published in *Research in Geophysics* shall rest in the Editor(s)-in-Chief appointed for an indefinite term by the Executive Committee. He shall have the aid and counsel of an advisory board representing the special fields of geophysics. This Board shall be designated by the President in consultation with the Editor(s)-in-Chief and the Executive Committee.

The *Geophysical Monograph* series will be published as members of the series develop and shall each be under the control of a special editorial board designated by the President, with the Executive Secretary serving as managing editor of the series.

Other publications that may develop shall be subject to approval by the Executive Committee under plans developed for their editorial management.

Non-members of the Union may subscribe to the *Transactions*, and purchase individual copies thereof, as well as other publications of the Union at rates approved by the Executive Committee of the Union.

Article 13(b) mentions *Transactions*, but there is no need to change.

By Laws

By-Law (2) Members of the Union, in classes (a) and (d) of Article 3 of the Statutes, shall pay dues, the amount for each year to be fixed by the Executive Committee of the Union. Members of class (e) shall pay dues of not less than $100 for each calendar year. Any Member or Associate, on payment of an amount to be fixed by the Executive Committee of the Union, shall be relieved of further payment of dues. Members of class (f) shall pay dues approximating the cost of a volume of the *Transactions* plus the cost of a volume of *Research in Geophysics*, the amount for each year to be fixed by the Executive Committee.

By-Law (3) Delete "Editorial and Publication."

By-Law (21) One copy of each issue of (a) the *Transactions*, (b) *Research in Geophysics*, (c) any published *List of Members and Officers*, and (d) any other publication which may be approved for free distribution to the membership by the Executive Committee of the Union, shall be sent to each Member, Associate, and Corporation Member whose annual dues for the calendar year have been paid by February 15; any person or organization newly elected as Member, Associate, or Corporation Member shall be sent without charge one copy of these publications beginning with the calendar year in which elected and for which dues have been paid. Each member on a retired basis, Member ex officio, and Corresponding Member shall be accorded this privilege also. Each Student Member shall receive one copy of each issue of the *Transactions* and one copy of each issue of *Research in Geophysics* for each year of paid membership.

Each person and organization in good standing in any class of membership may purchase any available publication of the Union at a discount from the printed price list to non-members. The General Secretary is authorized to establish discounts for sales of publications.

Appendix 3—Recommended Revision of the Structure of the Executive Committee of the American Geophysical Union to Provide More Effectively for Discharge of Responsibilities as the U. S. National Committee for the IUGG

(Not adopted; published as a basis for discussion—Ed.)

J. W. JOYCE, Chairman

LEASON H. ADAMS
LLOYD V. BERKNER
WALTER H. BUCHER
PERRY BYERLY
MAURICE EWING, *ex officio*
F. W. REICHELDERFER
A. NELSON SAYRE, *ex officio*
WALDO E. SMITH, *ex officio*

When first established under the National Academy of Sciences—National Research Council in 1919, the American Geophysical Union was designated as the U. S. National Committee for the International Union of Geodesy and Geophysics. The Executive Committee of the American Geophysical Union was to act as the Committee for Geophysics within the National Research Council.

At the time of its establishment, the total membership of the AGU was restricted to 65 persons. This limit was gradually increased until it had reached a hundred persons by 1929. In 1930 the limitation was completely removed and active efforts for increased membership began.

In order to meet operating expenses, including the support of an executive office and the publication of *Transactions of the American Geophysical Union*, annual dues are collected from individual members. These have been increased periodically in order to cover increasing costs as the activities of the AGU increased.

The prime function of the American Geophysical Union is to counteract the tendency toward specialization and is, therefore, diametrically opposed to that of societies serving individual fields. In so far as the AGU organizes meetings, collects dues, and issues publications, it has assumed, however, some aspects of a professional society.

The AGU's responsibility as the U. S. National Committee for the IUGG has continued in force but because of the increasingly large membership and the professional-society aspects of the Union the appropriate representational pattern as far as international matters are concerned has presented a problem. This may be subdivided into three parts:

(a) Now that several thousand persons are members of the American Geophysical Union, it is impossible to consider the entire roster as the U. S. National Committee as far as active participation of all individuals is concerned.

(b) It might be argued that the Executive Committee could serve as the IUGG National Committee, provided appropriate changes were made in the *Statutes and By-laws* as presently constituted. However, the procedures used to select the membership of the Executive Committee do not stress interest or experience in participating in international affairs, as exemplified by IUGG activities.

(c) Because certain agencies of the Federal Government are deeply concerned with geophysics, including the international aspects, it is essential that these agencies be represented on any body constituted to act as the U. S. National Committee for the IUGG.

These factors have resulted in having American delegations at IUGG General Assemblies who have been generally less prepared to deal with all the aspects of the various problems that arise at such a meeting when compared with delegations of certain other countries.

The need for effective representation at IUGG General Assemblies is becoming increasingly great. Experience has shown that many problems arise that are not necessarily of a pure scientific nature. These deal with matters of policy as far as the operations of the Union are concerned, matters of finance, or combinations of the two. Normally, questions of pure science do not present too great a problem. The importance of having effective representation will be particularly acute at the next General Assembly, now scheduled for Helsinki in 1960. This is due to very obvious moves on the part of certain countries to obtain as many elective officers as possible for their nationals, coupled with the fact that they will have large delegations in attendance.

The American Geophysical Union has discussed the need for more effective international representation over a period of several years, and in 1954 the Committee on International Participation, a standing committee of the AGU, was established to provide, as the name implies, recommendations and guidance for the strengthening of the position of the AGU in IUGG matters.

On January 10, 1958, several members of the Committee on International Participation met in the offices of the Associated Universities, Inc., at 10 Columbus Circle, New York City, to discuss what might be done to assure more active and effective participation of the American Geophysical Union in the international field that the AGU provides as a national, professional organization.

From the discussion that took place at this meeting there emerged a recommendation that the Executive Committee of the American Geophysical Union be reconstituted and renamed the Council of the American Geophysical Union. Briefly, the Council would be made up of the following:

(a) *Voting members*—(1) the elected officers of the AGU plus the Executive Secretary (four persons); (2) one member nominated by each section (this could be the section President or any other representative depending on the preference of the individual section) (eight persons); (3) one member nominated by each of the four government agencies having substantive interests in geophysics: Defense, Commerce, Interior, and the National Science Foundation (four persons); (4) four members-at-large nominated by the Section of Geophysics of the National Academy of Sciences (four persons); (5) U. S. officers to the IUGG or its Associations (variable number).

(b) *Ex-officio (non-voting) members*—(1) the chairmen of the various related divisions of the National Research Council (five persons); (2) the Director of the Office of International Relations, NAS-NRC (one person); (3) representatives from two government agencies having non-substantive interests in geophysics, Office of the Science Adviser, Department of State, and the President's Scientific Advisory Committee (two persons); (4) the chairmen of the various standing committees of the AGU (seven persons).

The names of all of the above persons would be placed in nomination to the NAS and their appointment would be made by the President of the Academy, as is now the case for the U. S. National Committee for URSI.

An Executive Committee would be selected from the Council to consist of three elected officers of the AGU and five members of the Council designated by the National Academy of Sciences from among the voting members of the Council. This Executive Committee would handle all but major policy decisions and could be brought together quickly and relatively inexpensively at times between the annual or semiannual meetings of the Council.

There is also a need to consider the AGU 'election cycle' in its relation to IUGG General Assemblies. Further, means must be considered for providing international experience and indoctrination to as many persons as practical. These are questions that will be given further study by the Committee on International Participation.

Prepared by:
Committee on International Participation
as a draft for consideration
by the Executive Committee, AGU

Special Announcements

NOTICE OF INTENT TO CHANGE THE BY-LAWS—Attention is called to the fact that at the meeting of the Executive Committee on May 4, 1958, initial steps were taken to amend the By-Laws as set forth in Appendix 2 of the minutes in this issue of the *Transactions*. In accordance with the statutes, notice is hereby given of the intent to change these. Subsequent action will presumably be taken in the fall meeting of the Executive Committee.

MEETING OF PACIFIC NORTHWEST REGIONAL GROUP—The Pacific Northwest Regional group will hold its Annual Meeting in Portland, Oregon, November 13–14, 1958, developing especially the theme of the International Geophysical Year. Interested persons should get into touch with the Chairman of the Regional Committee, Wilbur D. Simons, U. S. Geological Survey, 207 Federal Building, Tacoma 2, Washington.

MEETING OF THE *AAAS* IN WASHINGTON, D. C. DECEMBER 26–31, 1958—It is the plan that the AGU will join with the AAAS in this meeting, co-sponsoring various programs germane to geophysics, including one being arranged by the Section of Agriculture on the subject of water and agriculture, and sessions relating to the IGY.

PACIFIC SOUTHWEST REGIONAL MEETING TO BE HELD AT STANFORD UNIVERSITY, FEBRUARY 5–6, 1959—Plans are developing for the Pacific Southwest Regional meeting to be held at Stanford University. Interested persons should get into touch with Vito A. Vanoni, California Institute of Technology, Pasadena 4, California, or Joseph B. Franzini, Program Chairman, Civil Engineering Department, Stanford University, Stanford, California. It is the plan that at least hydrology, oceanography, and meteorology will be involved, and possibly other fields as well.

FORTIETH ANNUAL MEETING—The Fortieth Annual Meeting of the American Geophysical Union will be held in Washington, D. C., May 4–7, 1959, Monday through Thursday. This is the first call for titles and abstracts of papers and suggestions for symposia and other matters relating to the meeting. Send communications to P. H. Abelson, Chairman of the Committee on Meetings, 2801 Upton Street, N. W., Washington 8, D. C.; to the office of AGU, 1515 Massachusetts Avenue, N. W., Washington 5, D. C., or to the appropriate Section Secretaries or Program Chairmen as listed in the October 1957 issue of the *Transactions* pages 797–798.

NATIONAL ACADEMY OF SCIENCES

Number 13 • July 1958

IGY BULLETIN

A monthly survey by the U. S. National Committee for the International Geophysical Year. Established by and part of the National Academy of Sciences, the Committee is responsible for the U. S. International Geophysical Year program in which several hundred American scientists are participating and many public and private institutions are cooperating.

Preliminary Reports: Satellites 1958 Alpha and 1958 Gamma

Preliminary reports on data gathered by US-IGY satellites 1958 Alpha and 1958 Gamma were made to members of the National Academy of Sciences, the American Physical Society, and the Washington scientific community at a special meeting held May 1, 1958, at the National Academy of Sciences in Washington, D. C. The reports discussed high intensity radiation, micrometeorites, satellite temperatures, and atmospheric densities.

Observation of High Intensity Radiation

J. A. Van Allen of the State University of Iowa, on behalf of himself and his colleagues G. H. Ludwig, E. C. Ray and C. E. McIlwain, gave a preliminary report on radiation intensities measured with single Geiger tubes carried by satellites 1958 Alpha and 1958 Gamma.[1]

The counting rate of the Geiger tube in 1958 Alpha was transmitted continuously. Data were recorded only when the satellite was near one of the 16 receiving stations distributed over the earth (Table 1).

The data collected by 1958 Gamma were also telemetered continuously. In addition, a small magnetic tape recorder stored the data obtained during each entire orbit. Then, as the satellite passed near one of the receiving stations, a radio command from the ground caused these data to be read out.

A preliminary study of part of the data obtained from 1958 Alpha and from several interrogations of 1958 Gamma has been carried out, with the following results.

Reasonable cosmic ray counting rates have been obtained for altitudes below about 1000 km. In particular, a plot of intensity against height in the vicinity of California for the first two weeks in February, has been constructed. This curve, extrapolated down to altitudes previously reached by rockets, agrees with earlier data (Fig. 1).

At altitudes greater than about 1000 km, a very high intensity of radiation was encountered. This radiation was of such an intensity as to exceed the design capabilities of the electronic system for either direct transmission or for stored and played-back transmission. But the approximate magnitude of the intensity was determined by detailed study of the data and by laboratory calibration of the overall electronic system. It is estimated that for portions of the orbits of 1958 Alpha and 1958 Gamma, a Geiger tube of zero dead time would have been

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[1] J. A. Van Allen, G. H. Ludwig, E. C. Ray, and C. E. McIlwain, "Observation of High Intensity Radiation by Satellites 1958 Alpha and Gamma," *IGY Satellite Report Series, No. 3: Some Preliminary Reports of Experiments in Satellites 1958 Alpha and 1958 Gamma*, (National Academy of Sciences, Washington) pp. 73–92.

Table 1. *Receiving Stations*

Minitrack

Blossom Point, Maryland
Fort Stewart, Georgia
Antigua, British West Indies
Havana, Cuba
San Diego, California
Quito, Ecuador
Lima, Peru
Antofagasta, Chile
Santiago, Chile
Woomera, Australia

Microlock

Patrick Air Force Base, Florida
Earthquake Valley, California
Singapore
Ibadan, Nigeria
Temple City, California
Pasadena, California

Note: The Minitrack and Microlock radio tracking programs are under the direction of the Naval Research Laboratory and the Jet Propulsion Laboratory of the California Institute of Technology, respectively.

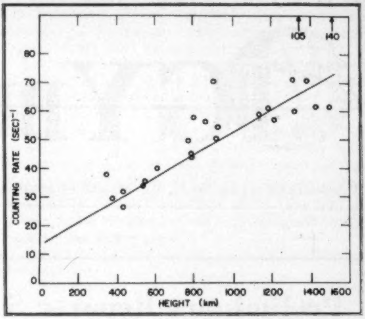

Fig. 1. *Graph of Variation of Cosmic Ray Intensity with Height in the Vicinity of California During the First Two Weeks of February 1958.*

producing over 35,000 counts/sec, or on the order of 1000 times the cosmic ray rate.

It is surmised that the newly discovered radiation is closely related to that previously found by the Iowa group above 50 km with rocket flights in the auroral zones.

Several important geophysical effects of this radiation are suggested. It is very likely closely related to auroras and geomagnetic storms. In addition, a rough calculation suggests that the radiation may be sufficiently intense to contribute important heating to the upper atmosphere. Also, the consequences in the production of atmospheric ionization, light, and radio noise are being investigated.

The directly observed effects in the satellite equipment are believed due to X-rays (bremsstrahlung) produced by the impact on the equipment of electrons of the interplanetary plasma which comes from the sun and encounters the environment of the earth.

Figure 2 exhibits a typical record of apparent counting rate against time obtained in an interrogation from San Diego at 1748 UT on the 28th of March. During the first 13 min (near perigee) the rate was well within the design capabilities of the system. Between 13 and 15 min the rate rose rapidly to exceed 128 counts/sec and remained above that value until 20 min had passed. Between 20 and 37 min the *apparent* counting rate was zero. This performance is interpreted as due to an equivalent rate exceeding 35,000 counts/sec (or 60 milliroentgens/hr of 80 kev X-rays)—i.e., a sufficient intensity of radiation to reduce the height of all Geiger tube pulses below the threshold level for triggering the scaling circuit. From 38 to 87 min the equivalent rate lay between 35,000 and 128 counts/sec, and again, near perigee of the orbit, from 87 to 107 min, the counting rate had the low value attributable to cosmic rays only.

A summary of counting rate data of this sort for several orbits of 1958 Gamma is given in Figure 3. Note that during the period March 28–31 the perigee was approximately at the most northerly latitude; hence, the altitude was low at high northerly latitudes and high at high southerly latitudes. Data from the continuous channels of 1958 Alpha and 1958 Gamma are concordant with each other and with data shown in Figure 3.

Preliminary interpretation of the data has been guided by the extensive knowledge which has been obtained by many rocket and balloon studies of the "soft radiation" in the

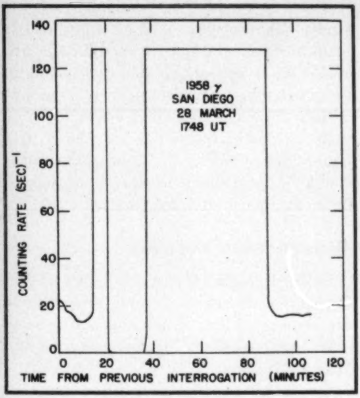

Fig. 2. *Record of Interrogation of 1958 Gamma.*

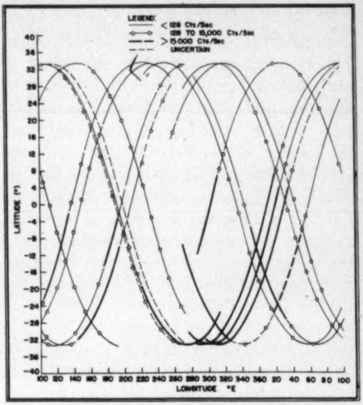

Fig. 3. *Counting Rate Data for 1958 Gamma Through Several Orbits, March 28–31, 1958.*

auroral zones. (See *IGY Bulletins* Nos. 3, 5, and 10.)

The satellite observations on which the present report is based are only a small portion of those available and now under systematic study.

Optical Studies

G. F. Schilling reported[2] on results from optical tracking of US satellites, based on work done by Charles A. Whitney, Theodore E. Sterne, and Luigi G. Jacchia at the Smithsonian Astrophysical Observatory. Preliminary analysis of the data obtained by visual observations and precise photographic observations has supplied information on the spin of 1958 Alpha, on air density at very high altitudes, and on the expected lifetime of 1958 Alpha.

Charles A. Whitney found[3] that 1958 Alpha, which was given a spin about its long axis during launching, now appears to rotate about its short axis, propeller-like. This conclusion is based on an observed variation of orbital acceleration.

Theodore E. Sterne has developed[4] a simplified formula for computing the air density at very high altitudes from the motion of artificial satellites. This formula, applied to orbital data inferred by Whitney through a critical study of visual and radio observations of 1958 Alpha, gives an air density value of about 1.5×10^{-14} gm/cm^3 at an altitude of 368 km. A cubic mile of air of this density would weigh only two ounces. Nevertheless, the density is about 15 times greater than that predicted in 1956 by R. A. Minzner and W. S. Ripley of the Air Force Cambridge Research Center.

Luigi G. Jacchia, using a formula developed by D. C. M. Leslie, and density values from the Smithsonian Interim Atmosphere of Sterne, Folkart, and Schilling, estimates[5] that 1958 Alpha will fall toward the end of 1962.

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[2] "Status Reports on Optical Observations of Satellites 1958 Alpha and 1958 Beta," ed. by G. F. Schilling, *op. cit.*, pp. 1–15.

[3] C. A. Whitney, "The Orbit and Variable Acceleration of Satellite 1958 Alpha," *op. cit.*, pp. 6–9.

[4] T. E. Sterne, "The Density of the Upper Atmosphere," *op. cit.*, pp. 10–14.

[5] L. G. Jacchia, "Life Expectancy of Satellite 1958 Alpha," *op. cit.*, p. 15.

Orbital Determinations

Joseph W. Siry, of the Naval Research Laboratory, reported[6] that the effect of atmospheric drag on the orbit of 1958 Alpha has been difficult to predict due to the fact that the drag force depends so strongly upon the angle of attack in the case of a cylindrical satellite of large fineness ratio, such as 1958 Alpha. The orientation of the satellite as a function of time has been difficult to predict at times, thus making the prediction of the orbit correspondingly difficult. However, preliminary estimates by NRL indicate that the lifetime of 1958 Alpha will be about 5 to 10 years and that the atmospheric density in the neighborhood of perigee, at about 370 km, is approximately 10^{-14} gm/cm^3. This is an order of magnitude greater than the value predicted for this altitude in 1956 by Minzner and Ripley.

Temperature Measurements

A. R. Hibbs and E. P. Buwalda, of the California Institute of Technology Jet Propulsion Laboratory, reported[7] on a passive solution of space temperature problems and on temperature measurements made by 1958 Alpha. Internal temperatures ranged from 0°C to 35°C inside the cylinder and from 5°C to 40°C inside the nose cone. Shell temperatures ranging from −25°C to 75°C were recorded.

The temperature control mechanism consists of a series of aluminum oxide stripes covering approximately 25% of the outer surface of the cylindrical section of the instrument compartment, and 30% of the outer surface of the nose cone. By both reflecting and re-radiating heat received from the sun and the earth, this coating maintained interior temperatures within the range needed to protect instrumentation from damage by heat or cold.

The experiment was designed only to study the problem of controlling instrument environment in a very small enclosure. However, it was noted that this technique provided temperature control in a satellite within the range of human survival. With more elaborate techniques, available in a larger space vehicle, the inner temperature could be controlled within quite narrow limits at almost any desired level.

Micrometeorite Densities

Edward Manring, of the Air Force Cambridge Research Center, reported[8] on the determination of micrometeorite densities in the satellites' orbits by himself and Maurice Dubin.

Two micrometeorite detection systems are used. One, called the gauge detector, is carried on both 1958 Alpha and 1958 Gamma. The individual gauges are one cm^2 in area and are wound with two layers of enameled wire 17 microns in diameter. Twelve of these gauges, covering an area of two square inches, are mounted in a circular pattern flush with the surface of the satellite's mid-section. When a micrometeorite of 5- to 10-microns diameter and travelling at meteor velocities, on the order of 25,000 mph, smashes into one of the gauges, the continuous circuit breaks and changes the transmitted signal.

The second detector, flown only on 1958 Alpha, consists of a crystal microphone mounted against the skin of the satellite and connected to an amplifier. When the satellite is struck by a solid particle, the impact pressure is converted into an electrical signal which is transmitted to the monitor stations.

About 10% of the microphone data and 50% of the gauge data from 1958 Alpha are available for study. Seven hits have been detected by the microphone, but after 32 days of flight only one gauge had registered an impact. The data indicates that the average influx of particles 10 microns in diameter or greater was not more than $10^{-3}/m^2/sec$ during the period of observation, and that the average influx of particles four or more microns in diameter was about $10^{-2}/m^2/sec$.

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[6] J. W. Siry, "The Determination of the Orbit of 1958 Alpha at the Vanguard Computing Center," *op. cit.*, pp. 16–23.

[7] A. R. Hibbs and E. P. Buwalda, "Satellite Temperature Measurements for 1958 Alpha-Explorer I," *op. cit.*, pp. 31–72.

[8] E. Manring and M. Dubin, "Satellite Micrometeorite Measurements," *op. cit.*, pp. 25–29.

Recapitulation

The above reports reflect preliminary results obtained from 1958 Alpha and, in the case of cosmic rays, from 1958 Gamma. Reports incorporating these preliminary results have now been sent to IGY World Data Centers and the Special Committee for the IGY. Analysis of the data from these satellites is continuing and will be the subject of further papers at an appropriate time.

There have been six satellites launched during the International Geophysical Year, three by the U. S. and three by the U.S.S.R.

The first USSR satellite, 1957 Alpha, is described in *Bulletin No. 5*; the second, 1958 Beta, is described in *Bulletin No. 6*. A report on 1958 Delta, the third USSR satellite, appears in the present issue of the *Bulletin*.

During the remainder of the US-IGY satellite program, satellite launchings will take place at the rate of about one a month, carrying a variety of experiments selected by USNC-IGY.

Third Soviet Satellite

The USSR launched its third artificial earth satellite, 1958 Delta, in the early morning of May 15, 1958. Following are selections from descriptive text issued on that date by Tass:

"In conformity with the program of the IGY a third artificial earth satellite was launched in the Soviet Union on May 15, 1958. The launching of the artificial satellite is intended for scientific research in the the upper layers of the atmosphere and cosmic space.

"The satellite entered its orbit inclined by 65 degrees to the plane of the equator. According to initial data, the greatest distance of the orbit from the surface of the earth is 1,880 kilometers [1168 mi]. The time of each revolution around the earth is 106 minutes. The satellite is separated from its carrier rocket which is following along a close orbit. . . .

"The third Soviet artificial earth satellite is conical in shape. The diameter of the base is 1.73 meters [5′8″] while its height is 3.57 meters [11′9″] not counting protruding aerials. The weight of the satellite is 1,327 kilograms [2925.5 lbs] including the weight of instruments for scientific research, radio measuring apparatus, and batteries weighing 968 kilograms [2134 lbs]."

Radio Moscow reported on May 15 that 1958 Delta ". . . carries equipment making it possible to carry out research along the entire orbit . . . [on] pressure and composition of the atmosphere in the upper layers; concentration of positive ions; the magnitude of the electrical charge of the satellite and the tension of the earth electrostatic field; tension of the magnetic field of the earth; intensity of the sun's corpuscular radiation; composition and variations of the primary cosmic radiation; distribution of photons and heavy nuclei in the cosmic rays; micrometeors; temperature inside and on the outside of the satellite."

Radio Moscow reported further that ". . . the satellite carries a multi-channel telemetric system with a high selectivity . . . [and] special transmitting installations which enable the carrying out of the measurements of the coordinates of its trajectory.

". . . it carries a transmitter continuously transmitting signals on 20.005 megacycles with a duration of 150–300 milliseconds and with a high power of transmission.

"The scientific and radio technical equipment installed in the satellite is controlled by a programming device. In addition to electrochemical sources of power, the satellite carries solar batteries. . . ."

On May 18, Pravda stated that the airtight satellite is made of aluminum alloys and is filled with gaseous nitrogen.

Radio signals from the satellite were first picked up abroad by the observatory of the University of Bonn, in Bonn, West Germany, at 6:15 am EDT, May 15, 1958. In this country the signals were first received by RCA Communications, Inc., at Riverhead, L.I., at 10:06 am EDT, May 15. First reception by a facility in the Naval Research Laboratory's Minitrack Network was at Woomera, Australia, at 8:35 am EDT, and, in this country, at the Ft. Stewart, Georgia, and Blossom Point, Maryland, Minitrack stations, both at 11:52 am EDT, May 15.

The first visual sighting of the satellite by a Moonwatch team in this country was reported by Robert C. Lehman, leader of the team at Harrisonburg, Virginia. Harvey Mast and Linford Gehman, members of this team, observed the satellite simultaneously at 9:03 pm EDT, May 15, 1958. The satellite was seen on its ninth revolution around the earth as an object of variable brightness, but of the first magnitude when at its brightest.

The first photograph of the satellite at a precision optical tracking station of the Smithsonian Astrophysical Observatory was taken by a Super Schmidt camera on Maui, Territory of Hawaii, at 0627 UT (2:27 am EDT), May 16, 1958.

Preliminary Report on the Thickness of Ice in Antarctica

The following report is based on material supplied by George P. Woollard, Department of Geology, University of Wisconsin.

Prior to the IGY, the only knowledge of the thickness of the Antarctic ice cap was obtained on the Norwegian-British-Swedish Expedition of 1949–52 to Queen Maud Land and on the earlier US expeditions led by Admiral Byrd. While the Byrd expedition measurements were all made in the vicinity of the Ross Ice Shelf, the Norwegian-British-Swedish expedition conducted a traverse from the sea ice onto the ice plateau, covering a distance of over 380 mi.

The feasibility of scientific over-snow traverse operations in the Antarctic was thus demonstrated; the results obtained constitute a milestone in the scientific exploration of Antarctica that ranks along with those of the Scott, Shackleton, Mawson, and Byrd expeditions. As a consequence, the US-IGY scientific program in Antarctica, along with that of other nations, includes seismic over-snow traverse operations as an integral component.

Information on ice thickness in Antarctica serves a number of scientific purposes. It sheds direct light on the glacial history of the Antarctic continent; in a broader sense it may reveal much of relevance to past and present world climatology. In a very different area, measurement of the flexure of the earth's crust under its enormous load of ice should yield data on crustal strength.

There are, in addition, practical as well as scientific considerations in studying the thickness of the Antarctic ice cap, as well as the Greenland, Ellesmere Island, Baffin Island, and other ice caps. If substantial portions of the Antarctic ice cap should melt, the volume of water released would profoundly influence sea level; some coastal cities might be completely submerged or develop into counterparts of Venice, with canals marking former streets. In fact, surveys indicate that certain former ice cap centers, such as Canada and Scandinavia, are rapidly rising, and many seaport towns that flourished when Rome was a world power are now marked only by their submerged ruins.(Carbon-14 dating shows that it has been only about 10,000 years since the retreat of the Wisconsin ice sheet—the last great advance of ice during the "Ice Age"—from the United States into Canada.)

Techniques of Measurement

To investigate the Antarctic ice cap, a multiple attack has been mounted utilizing the techniques of glaciology, seismology, gravity, magnetism, and geology, including photo-geology and submarine geology. In exposed-rock areas along the coasts it is possible to carry out geologic studies of the morainal material left at former positions of the ice front and to deduce the number of past advances and retreats of the ice. Similar information can be obtained from submarine cores taken from the adjacent sea floor.

From visual observation, and in particular from the study of air photos, considerable information can be obtained as to the former height of ice in valleys that may now be either ice-free or only partially ice-filled. The study of variations of ice density with depth, as observed from cores, in pits, and and from isotope dating of the ice at different depths, gives information concerning variations in the rate of ice accumulation in the recent past. While the actual thickness of ice can be obtained by drilling, this technique is both costly and slow. Only one deep boring, to study the nature of the ice rather than its depth, was included in the Antarctic program.

Seismic: The primary technique used for determining the ice thickness is that of seismology; it is based on the time it takes a sound wave to penetrate the ice and be reflected back to the ice surface from the underlying rock or water surface. This method, so long as the wave velocity in the ice is relatively constant, is as reliable for determining depth as direct drilling. Moreover, it costs only a fraction of the drilling cost, and a seismic measurement can be carried out in only a few hours compared to days, weeks, or months using a drill.

Although the time needed for a seismic measurement is small compared to drilling, it is lengthy compared to the time required for gravity or magnetic measurements, which can also be used for estimating ice thickness. These measurements can be completed in less than ten minutes. However, in contrast to seismic measurements, gravity and magnetic measurements are not significant by themselves. It is necessary first to compute a theoretical value of what the measurement should be in terms of the location and elevation of the particular observation site. The difference between this theoretical value and the observed value is used in estimating the ice thickness. Such differences are referred to as gravity and magnetic *anomalies*. As these anomalies are caused by horizontal variations in the factors measured, they form areal patterns of "highs" and "lows", which look very much like topographic contour maps.

Gravity: For effective use of gravity data, the latitude and elevation of the observation site must be known, as well as something about the density of the underlying crustal material. The force of gravity increases poleward owing to the shortening of the earth's radius as the poles are approached and to the reduced centrifugal force caused by the earth's rotation. In addition, there is a theoretical decrease of gravity with elevation, although it tends to be offset by the corresponding increase in mass of the material above sea level. In general, gravity values are related directly to the subsurface mass distribution, highs indicating excess mass and lows deficiency in mass.

Magnetic: In deriving magnetic anomalies, changes in the strength and inclination of the earth's magnetic field with both lati-

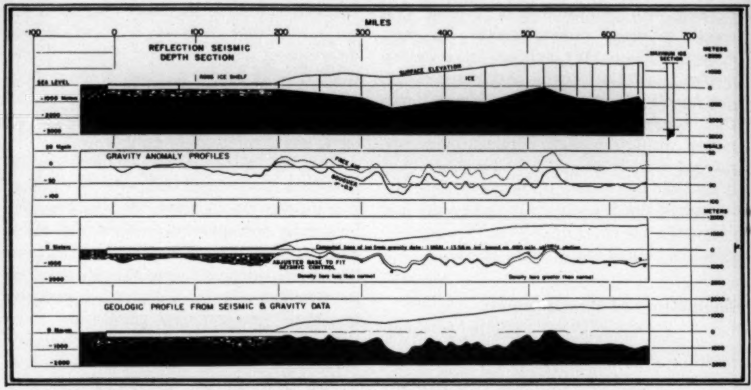

Fig. 4. *Seismic, Gravity, and Resulting Geologic Profile for Traverse Route from IGY Little America Station to IGY Byrd Station.*

tude and longitude must be considered as well as diurnal and secular, or long period, changes. To obtain magnetic anomaly values, corrections for these variations are applied directly to observed values. However, the derivation of magnetic anomalies is complicated by the fact that the pattern of highs and lows is influenced by the proximity of minor poles of magnetism induced on the boundaries of the disturbing rock mass by its geometry and its orientation in the earth's field.

Combined Techniques: By constructing profiles based on the anomaly patterns obtained by both gravity and magnetic techniques, it is possible to use the gradients on the flanks of individual highs and lows to calculate a minimum depth of origin of the anomalies. In the case of crystalline rocks underlying an ice sheet, this depth can be regarded as equivalent to the depth of the ice. Estimates of ice depth using gravity or magnetic techniques alone are far from exact, however, and errors of 20% or more are possible.

High magnetic anomalies are usually associated with gravity highs related to variations in the underlying crystalline rock, but magnetic effects resulting from variations in underlying rock configurations are small. Hence, it is possible to choose points for which the relationship between gravity-anomaly values and seismic depth measurements is significant. In this way, the gravity program can become an important adjunct to the seismic program for determining the the thickness of an ice sheet.

The method actually employed for determining the depth sections shown in the lower part of Figure 4 was to equate the seismically-determined depth below sea level at the 400-mile station to a type of gravity anomaly (Bouguer) value. This established the relation 1 mgal = 13.56m (or 44.32 ft) of ice. The Bouguer anomaly values were thus first interpreted as shown by the dashed line and then empirically adjusted on a sliding scale to account for apparent hori zontal variations in ice density, possible inclusion of morainal material, or regional variations in the kind of underlying rock. This gave the best overall fit to all of the seismic depth data. The final depth profile arrived at in this way is shown at the bottom of Figure 4. Although none of the depth

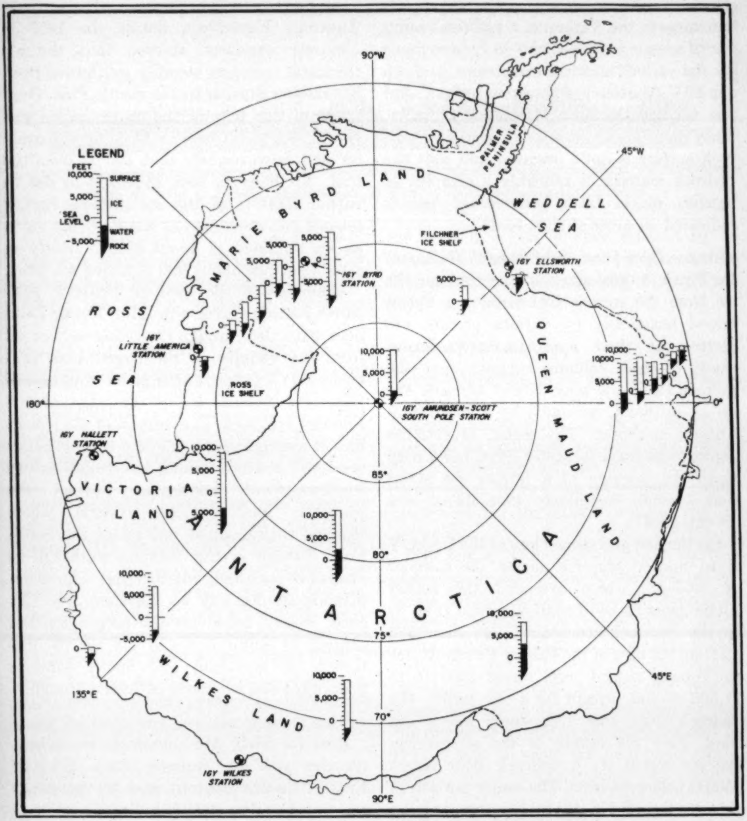
LEGEND
FEET
10,000
SURFACE
5,000
ICE
SEA LEVEL 0
WATER
-5,000
ROCK
90°W
45°W
180°
0°
135°E
45°E
90°E
85°
80°
75°
70°
MARIE BYRD LAND
PALMER PENINSULA
WEDDELL SEA
FILCHNER ICE SHELF
IGY ELLSWORTH STATION
IGY BYRD STATION
ROSS SEA
IGY LITTLE AMERICA STATION
ROSS ICE SHELF
IGY AMUNDSEN-SCOTT SOUTH POLE STATION
QUEEN MAUD LAND
IGY HALLETT STATION
VICTORIA LAND
ANTARCTICA
WILKES LAND
IGY WILKES STATION

Fig. 5. *Geologic Columnar Sections Showing Ice Thickness of Portions of Antarctica.*

values shown in the top profile, based on seismic data alone, have been significantly changed, the overall character of the profile has been materially modified by the inclusion of the gravity measurements.

The procedure used on the IGY Antarctic oversnow traverses, was, therefore, to take seismic depth measurements at roughly 30- to 50-mile intervals and gravity and magnetic observations, which require only a few minutes, at intervals of two to five miles. This combined program of seismic, gravity, and magnetic measurements supplies geological and geodetic data as well as glaciological data.

Results

While it is too early to give comprehensive results for the program to determine ice thickness in the Antarctic, a sufficient number of seismic measurements have been made by the various international teams and on the 1957–58 oversnow traverses to show that the average thickness is 8000 ft or more. They also indicate that the underlying bedrock surface is quite irregular and that the bedrock material is probably a complex of igneous rocks. Little sedimentary rock is indicated in areas studied to date.

Marie Byrd Land and Ellsworth Highland: In Figure 5, geologic columns through the ice from the surface to bedrock, as determined seismically by various groups, are plotted at their approximate positions. Study of these columns suggests that the Palmer Peninsula may extend beneath the ice as an island, separated by a strait from Antarctica proper. The region of extreme depth to bedrock in Marie Byrd Land may mark the position of a former sea strait that became completely ice-filled as the ice cap grew.

On the first and second legs of the US-IGY Byrd Station traverse during the summer of 1957–58, which extended the earlier Little America-Byrd Station profile (Fig. 4) to the Sentinel Mountains, less than 350 mi from the base of the Palmer Peninsula, ice thicknesses ranged from about 2000 ft to 11,500 ft and, except for a few peaks, the bedrock floor was everywhere below sea level. Near the middle of the second leg, the ice rested on a bedrock floor about 6500 ft below sea level. The major portion of the area included in this profile appears to be far enough below sea level to be under water even if the ice cover were removed and isostatic balance reestablished by uplift of the ice-freed surface. On the third leg, the bedrock floor was found to be rough and mostly above sea level, with nunataks (isolated peaks breaking through the ice) appearing in several places. Near the end of the third leg, an ice thickness of over 14,000 ft—the greatest ever recorded—was measured.

Weddell Sea to South Pole: Seismic soundings taken on the Commonwealth Trans-Antarctic Expedition during the 1957–58 Antarctic summer, showed that the ice thickness increases steadily southward from Shackleton Station to the South Pole. Over much of this part of the route the ice was about 6000 ft thick. At approximately 88°30′S, however, less than 100 mi from the Pole, the bedrock base appeared to rise to within 2000 ft of the ice surface. Earlier seismic measurements at the Pole had given an ice thickness of about 8300 ft overlying a rock surface about 900 ft above sea level.

Members of the 1957–58 US-IGY Ellsworth Station traverse in Edith Ronne Land detected a deep trough extending southward from the vicinity of the Argentinian Belgrano IGY Station, about 35 mi southeast of Ellsworth Station along the edge of the Filchner Ice Shelf. The bottom of the trough has an average depth of about 3500 ft below sea level. Farther inland, the trough swings southwestward, continuing beyond the southerly limit of the traverse, which reached within about 550 mi of the South Pole. Further seismic traverse work will be needed to ascertain whether this depression extends all the way to the Ross Sea. (An early theory based on the geography and geology of Antarctica and the nearby continents of Australia and South America postulated the existence of such a trough.)

Ross Ice Shelf: Measurements made both on the 1957–58 traverse from US-IGY Little America Station and by personnel remaining at the station indicate a more or less constant thickness for most of the shelf of about 1000 ft. Near the edge, however, thicknesses range from about 790 to 1050 ft, and at the Beardmore Glacier, along the poleward margin of the shelf, the ice is 1380 ft thick. The surface of the shelf is 165 ft higher at the Liv Glacier than at the Beardmore. Since the shelf is believed to be afloat in the Liv Glacier region, this constitutes a considerable increase in ice thickness. The only evidence of grounding of the shelf was on and around Roosevelt Island and at 83°30′S, 163°–169°W.

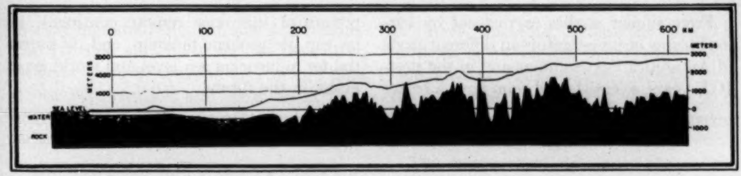

Fig. 6. *Seismic Profile Along Route of Norwegian-British-Swedish Traverse.*

Queen Maud Land: As shown in Figure 6, which is a seismic profile along the route of the Norwegian-British-Swedish expedition in 1948-52, the sub-ice surface is below sea level for at least 125 mi inland, and for a distance up to about 280 mi, there are still some areas with bedrock surfaces below sea level. The maximum ice thickness approaches 10,000 ft in the last 50 mi of the traverse. The configuration of the rock surface beneath the ice is quite irregular.

East Antarctica: During the past Antarctic summer, a party from the Australian Mawson IGY Station, at 67°36′S, 62°53′E, conducted a continuous seismic traverse for more than 400 mi south from the station. About 200 mi inland, over a point where the sub-ice surface rose to a height of 3000 ft above sea level, the ice was about 5000 ft thick. Normal ice thicknesses in this region and to the south were greater. In most places along the traverse route, the bedrock surface was above sea level.

At the USSR Vostok IGY Station, near the south geomagnetic pole almost 1000 mi into the interior of the continent, an ice thickness of 8700 ft was reported. The bedrock surface beneath the station is 2300 ft above sea level.

At station C (77°22′S, 139°48′E) of the US-IGY airborne traverse conducted in Victoria Land during the 1957–58 summer season, a possible ice thickness of 12,500 ft was measured. Distinct ice-bottom reflections were not obtained, however; it is surmised that the bottom topography in this region is too rough to serve as an efficient seismic reflector. Figure 5 shows an ice thickness of more than 9000 ft at the French Charcot Station, a few hundred miles north of station C. The bedrock surface beneath the Charcot Station is nearly 3000 ft below sea level.

Crustal Flexure

Analysis of the anomaly profiles in Figure 4 suggests crustal warping inland, with sufficient displacement of denser subcrustal material to establish isostatic equilibrium for the superimposed load of ice. It also indicates that there is no appreciable crustal flexure within the border area of the ice plateau.

The fact that the rock surface at the base of the ice is either close to sea level or well below it throughout much of Antarctica suggests considerable flexure of the continental crustal material. It is hoped that during the post-IGY period it will be possible to obtain extended gravity and seismic measurements in the offshore area so that the degree of crustal displacement caused by the ice load on shore can be directly evaluated.

Reduction of New Data

At the Antarctic Gravity and Seismological Data Reduction Center at the University of Wisconsin, profiles are now being prepared for the various traverses carried out during the 1957–58 summer season in the US-IGY Antarctic Program. The center is manned by personnel who took part in these traverse operations. Now working there are E. C. Thiel and J. C. Behrendt, from IGY Ellsworth Station, E. S. Robinson and H. F. Bennett, from IGY Little America Station, and N. A. Ostenso, from IGY Byrd Station.

From similar studies carried out by various teams of investigators in different parts of Antarctica next summer and in the post-IGY years, scientists will soon have a better picture of this once remote continent, its ice cap, its geologic makeup, and its potential for influencing sea level and world geography in the future.

Rocket Results at Fort Churchill

By July 1, 1958, a total of 116 rockets had been fired in the US-IGY Rocket Program. This number includes rockets fired in programs conducted at Fort Churchill (21 Aerobees, 20 Nike-Cajuns); White Sands (two Nike-Cajuns, one Aerobee, one Nike-Asp); Alamogordo, New Mexico (two Aerobees); Point Mugu, San Nicolas Island, California (14 Nike-Deacons, one Nike-Asp); a shipborne operation in the Arctic (18 Rockoons); and a shipborne operation in Pacific and Antarctic waters which was concluded in mid-November 1957 (36 Rockoons). (See *IGY Bulletins 7*, *5*, and *11* for accounts of the latter 3 operations.)

The major effort of the US-IGY rocket program is centered at the rocket launching facilities especially constructed for the IGY in cooperation with the Canadian Government and the Canadian IGY Committee at Fort Churchill, Manitoba, Canada. Thirty-three of the 41 launchings here have resulted in good rocket performance and satisfactory data. In addition, 6 of 7 rockets fired from the same facility prior to the IGY produced satisfactory experimental data. During a single 48-hour period in January 1958, in the midst of the Arctic winter, 5 rockets were successfully launched.

Experimental Results

Table 2 lists the rockets fired from Fort Churchill, the instrumentation carried, the performance of the rocket, and the success of the experiment. The major scientific results for each experiment are summarized below.

Participating research organizations include the Air Force Cambridge Research Center, University of Michigan, Naval Research Laboratory, Signal Engineering Laboratories, State University of Iowa, and the Army Ballistic Research Laboratories.

Ion Composition of the Arctic Ionosphere: Three Aerobee-Hi rockets instrumented with radio-frequency mass spectrometers were launched to peak altitudes of from 200–250 km. Positive and negative ions were detected on all three flights. It was found that ionized nitrogen oxide was a very important constituent of the ionosphere below 200 km and that during the daytime ionized molecular oxygen is present below 100 km and ionized atomic oxygen is present above 150 km. This new information on the electrical composition of the lower ionosphere is of great importance to theoretical studies of the interaction of solar radiation and atmospheric molecular constituents.

Structure of the Arctic Upper Atmosphere: Results from two Aerobee-Hi rockets launched during 1956–57 have been compared with structural information derived from rockets launched during 1953–54 from high altitude skyhook balloons. Tentative results indicate that at 200 km the summer daytime atmosphere density at 59°N is 2.5 times the winter daytime value; and 20 times the winter nighttime value. The summer daytime value is 6.5 times the corresponding value at White Sands, New Mexico.

At lower altitudes, between 30–45 km,

density measurements indicate that seasonal and latitude variations are less than 10%, while summer pressure measurements show Arctic temperatures and pressures at these altitudes to be significantly higher than values determined at lower latitudes.

Diffusive Separation of Gases in the Upper Atmosphere: Diffusive separation of gases under gravity in the ionosphere plays an important role in the modification of the composition of the upper atmosphere. An experiment carried out during the Arctic winter night measured the composition of the upper atmosphere between 105–240 km by means of a radio-frequency mass spectrometer. Ninety-six spectra were obtained on the ascent of the rocket and seven spectra on the descent of the rocket. Analysis of these spectra shows diffusive separation of argon and nitrogen in the region 112–150 km. Data obtained on the general composition of the upper atmosphere over the regions covered in flight also show the presence of atomic oxygen.

Meteorological Soundings: Some 30 upper atmosphere rocket soundings measured temperature, pressure, density and winds. Experiments have included the freely-falling sphere for measuring densities, the rocket-grenade experiment for the measurement of temperatures and winds, and several aerodynamic techniques for measuring pressures and densities in the supersonic flow.

Many of these rockets attained altitudes greater than 200 km, and thus the first density measurements made at high latitudes were recorded. Launchings were made during both summer and winter, day and night. The resulting data indicate that the density of the high atmosphere is under strong solar control. There appear to be a latitude effect, a seasonal effect, and a strong diurnal effect; none of these effects appear at lower altitudes at Fort Churchill or at lower latitudes.

A firing at Fort Churchill measured the first atmospheric temperature maximum at an altitude of about 60 km. Normally this maximum is found below 50 km at lower latitudes, indicating that, at northern latitudes, the temperature rise is more gradual. (Temperatures decrease up to the stratosphere, rise during the next 20 to 30 km, decrease through the next 30 km, and then rise again.)

The temperature data have shown that the winter measurement is characterized by low temperatures below 50 km. The summer results, by contrast, show extremely low temperatures at 30 km.

Winds measured at Fort Churchill have the characteristic summer-winter difference which has been observed in lower latitude measurements. The winds are weak and from the east in the summer, very strong and from the west in the winter.

Electron Density Measurements: Four Aerobee-Hi rockets have been launched to study the ionosphere above Fort Churchill. The resultant data show the ionosphere to be a single layer, strong during the day and weak at night. Two of the rockets made important discoveries. These launchings took place during "polar blackouts," periods of disrupted communications at high latitudes. The rockets have shown that the "blackout" is due to a very dense and low "D" region of the ionosphere. It has been determined that this dense region exists at a significantly lower altitude, and with a much greater density, than is found at lower latitudes. These data will be especially useful for effecting improved radio communications.

Horizon Studies—Water Vapor Structure: On March 24, 1958, the first of a planned series of five Nike-Cajun rockets was fired to obtain photographs of the horizon at a high latitude geographical location. These photographs, which show the haze surrounding the earth as a band at the horizon, reveal water vapor structure as bright lines in the haze horizon band.

Tentative results from this flight show a single tropopause structure at Fort Churchill with little evidence of fine structure. In addition, it is evident that the brightness profile

Table 2. *US-IGY Rocket Results at Fort Churchill to 1 June, 1958*

IGY Rocket No.	Launching Date	Experiment	Results		
			Experiment performance	Rocket performance	Peak altitude (Miles)
			Pre-IGY		
AM 6.31	20 Oct 56	PTD	Sat	Normal	70
AM 2.21	23 Oct 56	PTD	Sat	Normal	90
NN 3.02	5 Nov 56	AP	Unsat	Unsat	Unknown
SM 1.01	12 Nov 56	TW	Sat	Below Pred.	42
NN 3.07	15 Nov 56	AP	Sat	Below Pred.	80
NN 3.12	17 Nov 56	PD	Sat	Normal	130
NN 3.17	20 Nov 56	CIC	Sat	Normal	158
			During IGY		
NN 3.08F	4 Jul 57	CD	Sat	Normal	160
NN 3.09F	4 Jul 57	CD	Limited Data	Unsat	10
SM 1.02	22 Jul 57	TW	Sat	Normal	57
SM 1.03	23 Jul 57	TW	Sat	Normal	54
NN 3.13F	29 Jul 57	PTD	Sat	Normal	131
AM 6.32	30 Jul 57	PTD	Unsat	Unsat	14
SM 1.04	12 Aug 57	T	Sat	Below Pred.	46
SM 1.05	19 Aug 57	TW	Sat	Normal	58
RPX 6.X1	23 Aug 57	Test	Sat	Normal	70
SS 6.38	24 Aug 57	TW	Unsat	Unsat	Unknown
SM 2.06	25 Aug 57	TW	Sat	Normal	81
II 6.22F	27 Aug 57	AP, C	No Data	Unsat	Unknown
II 6.23F	30 Aug 57	AP, C	Limited Data	Normal	70
AM 4.01	1 Sep 57	PTD	Sat	Sat	99
SS 6.39	10 Dec 57	TW	Unsat	Unsat	Unknown
SM 1.07	11 Dec 57	TW	Sat	Normal	53
SM 1.08	14 Dec 57	TW	Sat	Normal	50
AM 6.34	14 Dec 57	PTD	Unsat	Unsat	Unknown
AM 6.02	25 Jan 58	PTD	Sat	Normal	100
NN 3.03F	25 Jan 58	AP, M	Sat	Normal	112
SM 1.09	27 Jan 58	TW	Sat	Normal	61
SM 2.10	27 Jan 58	TW	Sat	Normal	94
AM 6.36	27 Jan 58	PTD	Sat	Normal	80
AM 6.03	29 Jan 58	PTD	Sat	Normal	100
NN 3.10F	3 Feb 58	CD	Sat	Below Pred.	86
NN 3.11F	4 Feb 58	CD	Sat	Normal	146
II 6.24F	13 Feb 58	AP, C	Sat	Below Pred.	80
II 6.25F	16 Feb 58	AP, C	Sat	Below Pred.	75
NN 3.18F	21 Feb 58	CIC	Sat	Normal	140
II 6.26F	21 Feb 58	AP, C	Sat	Below Pred.	80
NN 3.14F	24 Feb 58	PTD	Sat	Below Pred.	128
AM 6.37	24 Feb 58	PTD	Sat	Normal	89
II 6.27F	24 Feb 58	AP, C	Sat	Below Pred.	80
RPX 6.X2	26 Feb 58	Test	Sat	Unsat	Unknown
AM 6.04	4 Mar 58	PTD	Failed	Unknown	Unknown
AM 6.05	4 Mar 58	PTD	Sat	Normal	105
NN 3.04F	15 Mar 58	AP	Sat	Below Pred.	78
NN 3.05F	22 Mar 58	AP	Sat	Normal	104
NN 3.19F	23 Mar 58	CIC	Sat	Below Pred.	128
OB 6.08	24 Mar 58	HS	Sat	Normal	74
AM 6.38	24 Mar 58	PTD	Sat	Normal	85

Experiment Code

P—Pressure
T—Temperature
D—Density
W—Winds
M—Magnetic Field
AP—Auroral Particles
CIC—Chemical and Ion Composition
HS—Horizon Study
C—Cosmic Ray Intensity
CD—Charge Density in Ionosphere

across the haze horizon increases in contrast ratio much more rapidly as a function of altitude than brightness profiles witnessed at lower latitudes.

A special parachute recovery system was developed for these flights. This was the first firing of a recovery system in this vehicle in an Arctic region. The 85-pound nose section was recovered undamaged from an altitude of 74 miles.

Field Operations at Fort Churchill

A significant reason for the success of the Fort Churchill IGY rocket sounding program has been the unique construction and operation of the range facilities under Arctic conditions. Since many of the IGY rocket research organizations are laboratories within the Department of Defense, an Interservice Support Coordinating Group was established to coordinate logistic and range facilities provided by the three services. The group consists of representatives of the Army Signal Corps, the Air Force and the Navy, all under the supervision of a representative of Army Ordnance, which assumed responsibility for the establishment and operation of the range.

The launching complex itself consists of an Aerobee tower, movable in any direction to compensate for winds, a building to house the Nike-Cajun (or DAN) launcher, preparation buildings, telemetering trailers, a blockhouse, a generator building, a helium building, and connecting tunnels. Also included and installed were two radars, range safety plotting boards and a command transmitter, a frequency monitoring station, a timing system, meteorological and wind ballistic balloon launching facilities and sites, and a complete range communications system.

Numerous instrumentation sites are installed at various points throughout the military reservation at Fort Churchill. Included are a four-station DOVAP tracking system and ballistic cameras, two telemetering trailers, two ionosphere stations, and a network of sound-ranging geophones. (See Fig. 7)

With few exceptions, the rockets fired at Fort Churchill have been equipped with radio doppler (DOVAP) tracking beacons. These beacons serve as telemeter transmitters in addition to their primary function in the tracking system. Excellent trajectory data have been obtained on all rockets either to peak altitude or to break-up on reentry. This tracking system is in use at most of the major firing ranges in the United States and in other countries. The operational record at Fort Churchill indicates that the precision of the data is such that errors

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IGY Number Code Example: A M 2 21 F

Place 1. Directing Agency
Place 2. Instrumenting Agency
Place 3. Type of Vehicle
Place 4. Directing Agency's Serial Number
Place 5. Vehicle purchased with IGY funds through the National Science Foundation

Symbols used in places 1, 2

A. Air Force Cambridge Research Center (AFCRC)
B. Ballistic Research Laboratories, Aberdeen (BRL)
I. State University of Iowa (SUI)
M. University of Michigan (MICH)
N. Naval Research Laboratory (NRL)
O. Army Ordnance
S. Army Signal Corps Engineering Laboratories (SEL)

Symbols used in place 3

1. Aerobee, Model RTV-A-1a (AJ10-25)
2. Aerobee, Model RTV-N-10c (AJ10-34)
3. Aerobee, Model RV-N-13c, called Navy Aerobee-Hi
4. Aerobee, Model AJ11-6, called Air Force Aerobee-Hi
5. Balloon-rocket combination, called Rockoon
6. Nike-Cajun rocket combination

Other

RPX. Rocket Project, Experimental

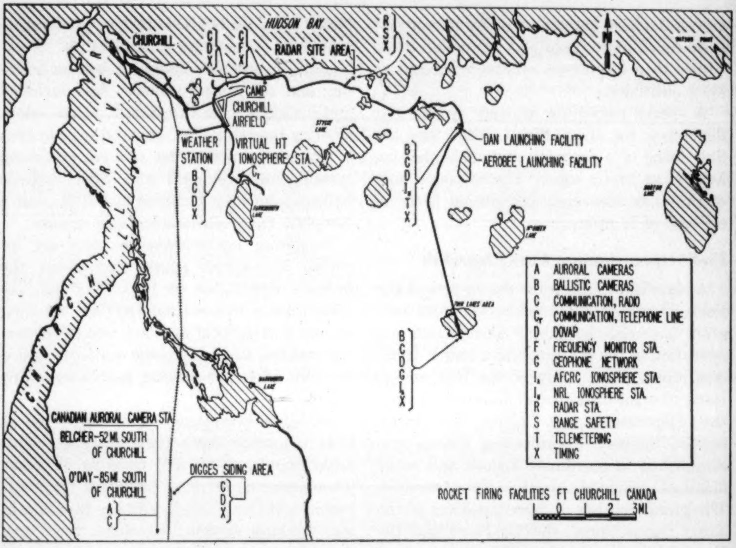
HUDSON BAY
CHURCHILL
C D X
C F X
RADAR SITE AREA
R S X
CAMP CHURCHILL AIRFIELD
WEATHER STATION
VIRTUAL HT IONOSPHERE STA.
C_T
B C D X
B C D I_n T X
DAN LAUNCHING FACILITY
AEROBEE LAUNCHING FACILITY
B C D G I_s X
CHURCHILL RIVER
CANADIAN AURORAL CAMERA STA.
BELCHER–52 MI. SOUTH OF CHURCHILL
O'DAY–85 MI. SOUTH OF CHURCHILL
A C
DIGGES SIDING AREA
C D X
A AURORAL CAMERAS
B BALLISTIC CAMERAS
C COMMUNICATION, RADIO
C_T COMMUNICATION, TELEPHONE LINE
D DOVAP
F FREQUENCY MONITOR STA.
G GEOPHONE NETWORK
I_s AFCRC IONOSPHERE STA.
I_n NRL IONOSPHERE STA.
R RADAR STA.
S RANGE SAFETY
T TELEMETERING
X TIMING
ROCKET FIRING FACILITIES FT CHURCHILL CANADA
0 1 2 3MI.

Fig. 7. *Instrumentation Site Locations at Fort Churchill.*

in altitude of less than 100 feet at rocket peak and in velocities of less than one foot per second have been commonplace. Such accuracies were required in many of the experiments.

An extremely important feature of the Fort Churchill IGY rocket program has been the very close cooperation of Canadian personnel. The Canadian IGY Committee and government agencies have provided most valuable assistance in the establishment and operation of this rocket range.

Life Sciences Experiments Using Earth Satellites

The possible uses of earth satellites for experiments in the life sciences were discussed by some 350 engineers and life scientists, representing both public and private institutions, at a symposium held in Washington, D. C., May 14–17, 1958. The symposium was planned and arranged by a 14-member steering committee appointed by Detlev W. Bronk, President of the National Academy of Sciences. The American Institute of Biological Sciences and the National Science Foundation joined the Academy in sponsorship of the meeting. Richard W. Porter, Chairman of the US-IGY Technical Panel for the Earth Satellite Program, served as symposium chairman.

The meeting had three basic objectives: (a) To stimulate thinking that will lead to a sound research program using earth satellites to achieve broad objectives in the life sciences, with an ultimate goal of manned space flight; (b) to exchange information concerning the technical feasibility and scientific importance of various experiments on living organisms in the satellite environment; and (c) to discuss methods and techniques for conducting such experiments, including associated laboratory work.

Some discussion of current proposals for projects in the rocket, satellite, and space areas was arranged for life scientists participating in the symposium. There was additional discussion of engineering considerations in satellite research and of facilities that may become available to life scientists in the future.

Two sessions of the meeting were devoted to discussions of experiments in basic biology in the satellite environment. At another session, biophysical instrumentation required for research in the satellite environment was discussed. Subsequent sessions covered animal physiology in satellites, behavioral research involving both animals and man, and human physiology in space vehicles. The final session was devoted to discussion of funding of biological research using satellites. Opportunity was provided during the symposium for brief papers.

It is planned to make the proceedings of the symposium available to the public and the scientific community by publication at an early date. It is hoped that this publication will form the basis for a future US program of biological research using artificial satellites as a tool.

IGY Bibliography

Beginning with this issue, each Bulletin *will carry as broad a selection of bibliographic entries relating to IGY programs and findings as space permits. The references are selected largely from an IGY bibliography under preparation in the Science Division of the Library of Congress. This month's list includes a section covering the status as of May 1, 1958, of the* Annals of the International Geophysical Year.

Selected Bibliography

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Status of IGY Annals

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Vol. I, History of IGY (in preparation).

Vol. II, Reports of IGY Conferences (in preparation).

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  Part I, "Ionospheric Vertical Soundings," pp. 1-167.
  Part II, "The Measurement of Ionospheric Absorption," pp. 173-226.
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  Part III, "Longitudes and Latitudes," pp. 143-201.
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Vol. VI, Instruction Manual for Rockets and Satellites (in press).

Vol. VII, List of IGY Stations (in press).

Vol. VIII, National Programs and Guide to World Data Centers (in press).

The *Annals* are published by the Pergamon Press, Ltd., 122 East 55th Street, New York 22, N. Y., and 4 & 5 Fitzroy Square, London, W.1.

IGY Rocket and Satellite Report Series

Data derived from results of experiments and observations conducted in connection with the IGY Rocket and Satellite Program are being issued in two series of reports published by the IGY World Data Center A subcenter for Rockets and Satellites. The two series are:

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(b) IGY Rocket Report Series

The subcenter has been established at the National Academy of Sciences by IGY World Data Center A, located in the United States (Data Center B is in the USSR and Data Center C is located in Western Europe and the Far East.)

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No. 4—Observational Information on Artificial Earth Satellites Based on Orbital Observations
No. 5—Radio Observations of Soviet Satellites 1957α2 and 1957β1 (July 1958)

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A monthly survey by the U. S. National Committee for the International Geophysical Year. Established by and part of the National Academy of Sciences, the Committee is responsible for the U. S. International Geophysical Year program in which several hundred American scientists are participating and many public and private institutions are cooperating.

Quaternary Glaciation: McMurdo Sound Region

This report is based on material furnished by Troy L. Péwé, Glacial Geologist, USNC-IGY, College, Alaska.

A common objective of many IGY studies in the Antarctic is to learn something of the history of the Antarctic ice cap. Meteorologists are gathering data on the whole range of ice-air-sun relationships. Glaciologists are studying the history of the continent in samples of snow and ice obtained from pits and by deep core drilling. Glacial geologists are seeking to fit the rock material deposited by glaciers into the geologists' calendar of the last few thousands of years.

One of the most obvious methods of learning something about the history of the ice cap is to study the evidences of past fluctuations of the margin of this continental glacier. Today, the ice cap spills into the sea or terminates at the sea around most of the continent. The record of ice-front fluctuations, then, lies mostly under water and at the present time is relatively inaccessible. In some areas, however, considerable ice-free land is present and the record of fluctuations of the fronts of both small and large glaciers is preserved.

One of the best localities to study the record of advances of both the outlet glaciers from the ice cap and the small alpine, or mountain, glaciers not connected with the ice cap is in the ice-free area surrounding McMurdo Sound. McMurdo Sound is at the southwest corner of the Ross Sea at 165°E, 77°S, in the shadow of the Royal Society Range (see Fig. 1).

Troy L. Péwé, glacial geologist, and Norman R. Rivard, assistant glacial geologist, spent most of the period December 1, 1957–February 10, 1958, in this ice-free area. Support in transporting men and supplies to the field by helicopter was provided by the US Naval Air Facility at McMurdo Sound. Aerial survey flights were made in US Navy aircraft. Glacial deposits were examined on Ross Island, Black Island, Brown Island, Mt. Discovery, and in the dry, ice-free valleys along the west side of McMurdo Sound—from Mt. Dromedary on the south to Gneiss Point on the north.

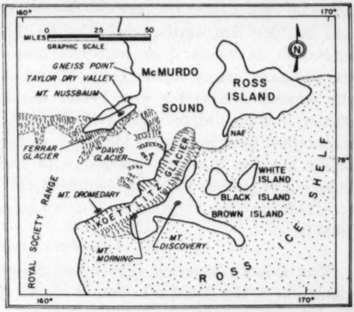


Fig. 1. *McMurdo Sound Region, Antarctica*

Glacial History

Evidence of at least three major Quaternary glaciations, each less extensive than the former, was found in the McMurdo Sound region. (A glaciation denotes a glacial advance and retreat represented by deposits and land forms distinguishable from those of different ages. The Quaternary period is the last million years of geologic time. It includes the Pleistocene and Recent epochs.)

Oldest Glaciation: The earliest glacial advance recognized in the region is indicated by patches of weathered rock material deposited by the glacier high on ridges and on elevated flat areas, such as those on both sides of the lower end of Davis Valley and near Mt. Nussbaum in Taylor Dry Valley. These deposits are 2000 ft above the valley floor. Many boulders have been abraded to the level of the ground surface by fine rock particles borne by the ever-present, strong winds. Ice of this glaciation filled all the valleys in the area and must have choked McMurdo Sound, banking at least 2000 ft up onto the surrounding terrain.

Intermediate Glaciation: Deposits of a succeeding glaciation are distributed widely around the Sound. Well-preserved but considerably wasted moraines (glacier-deposited rock material) of both outlet and alpine glaciers mark the extent of this glaciation. No sharp ridges exist and the moraines do not have cores of ice. Stones shaped by wind abrasion (ventifacts) are very well developed and boulders are wind-eroded. During this glaciation, in which there were two major ice advances, many alpine glaciers reached the expanded Koettlitz and Ferrar outlet glaciers; these alpine glaciers probably maintained their individual identities. Other alpine glaciers, however, merged with the huge outlet glaciers to fill the southern part of McMurdo Sound to an elevation of about 1000 ft.

Most Recent Glaciation: The latest major glaciation in the McMurdo Sound region is represented by the well-preserved, ice-cored moraines of the Koettlitz glacier. These are rich in volcanic materials. It is also represented by fairly well-preserved, granite-rich moraines of the alpine glaciers. Moraines of the large glaciers are characterized by many lakes and by fresh, or relatively unwasted, knob and kettle topography. The drift of small alpine glaciers is fresh but mainly represented by a thin boulder-filled clay. Ventifacts are well developed on moraines not cored with ice.

Lakes formed by blockage of valleys by glacial ice or moraines, but now drained, also existed during this latest major glaciation. The number and position of deltas in these former lakes suggest two, or possibly three, periods when the glaciers stood still or made only minor advances during this glaciation. Most alpine glaciers did not reach the sea or merge with the outlet glaciers; however, Koettlitz and Ferrar Glaciers pushed into McMurdo Sound.

Adjacent to many of the alpine glaciers are small, sharp-crested, ice-cored lateral moraines 50 to 100 ft high. These moraines are near the lower ends of the glaciers and in some places are compound. The moraines are extremely fresh and may represent minute ice advances during the last few centuries.

Regimen of Antarctic Glaciers

Comparison of the present positions of the fronts of many glaciers with their positions as shown in photographs taken 46 years ago by Griffith Taylor, a member of Scott's last expedition, reveal that little or no change has taken place in this interval. This is in sharp contrast to the movement of glacier fronts in both northern and southern temperate latitudes and supports the assumption that Antarctic glaciers have a sluggish regimen.

Conclusions

Examination of the glacial deposits in the McMurdo Sound region reveals that both the alpine and outlet glaciers have fluctuated widely in thickness and extent in the geologic past, and at least three major Quaternary glaciations are recorded. The two groups of glaciers are now independent, but in the past they merged to fill McMurdo Sound with ice. At several times in the later part of the Quaternary Period many large lakes formed when valleys were blocked by glaciers or glacier moraines. These valleys now contain only small lakes, but high-level shorelines, deltas, lake clays, and evaporite deposits—soluble salts precipitated upon evaporation of a water body—remain to attest to the former existence and extent of these lakes. (One evaporite was identified as mirabilite, or Glauber's salt, $Na_2SO_4 \cdot 10\ H_2O$.)

Although a Quaternary chronology of glacial advances and retreats, formation and destruction of lakes, and changes in sea level is recorded in the glacial materials of the McMurdo Sound region, no direct connection has yet been made with the glacial chronology elsewhere in the world.

Meteorological Rocket Soundings in the Arctic

This report is abstracted from material furnished by W. G. Stroud, US Army Signal Research and Development Laboratory, Fort Monmouth, New Jersey.

During the IGY, rocket soundings are measuring temperature, pressure, density, and winds at high altitudes in the Arctic. By the end of the IGY these soundings should yield enough data to provide a good understanding of the dynamic processes of the upper atmosphere.

Most of the US-IGY meteorological rocket soundings in the Arctic program are made from Fort Churchill, Canada (see *Bulletin 13*).

In the planning of the experiments at Fort Churchill, a guiding principle was that only proven rocket-borne techniques would be used. All techniques for observation used have been tested at the White Sands Proving Ground and have yielded significant data. The measurements have the added value of being made with the same methods in different geographic locations. Each of the techniques used, with a summary of observations, is described below.

Table 1 lists all experiments in the Arctic program and the locations and number of launchings up to June 1958. All of the US experiments, except that using the grenade technique, depend on telemetry (radio transmission of data to ground stations) from the rocket. Interpretation of most data depends on a knowledge of the trajectory of the rocket as obtained by the DOVAP system. DOVAP (Doppler-Veloc-

Table 1. *Arctic Meteorological Rocket Soundings*

Experiment	No. Launched	Location	Time
Sphere	8	North Atlantic & Churchill	W, D
Grenade	10	Churchill	W, S D, N
Aerodynamic	6	Churchill	W, S D, N
Gauge	3	Churchill	W, S D, N
USSR	6	Franz Joseph Land	W, D

Time code: W—Winter; S—Summer; D—Day; N—Night.

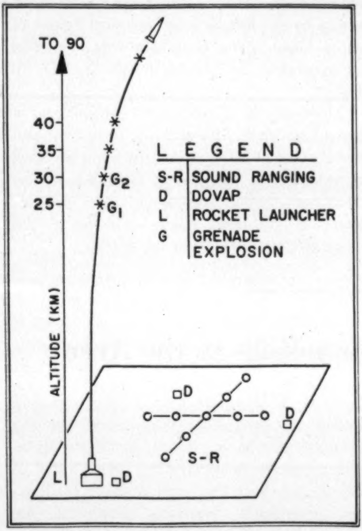


Fig. 2. *Instrumentation for the Grenade Experiment. The DOVAP stations track the rocket. The microphones determine azimuth and elevation of sound waves originating in high altitude grenade explosions.*

ity-And-Position) establishes the trajectory by measuring phase differences in the arrival of radio signals from the rocket at three locations (see Fig. 2). All data given here are preliminary and subject to modification.

The Freely-Falling Sphere Experiment

Technique: This method of measuring the density of the atmosphere was developed by a University of Michigan group under L. M. Jones, using first Aerobees and later Nike-Cajuns. In the present procedure, a 7-inch-diameter, 9-lb sphere is carried aloft. This is ejected from the Nike-boosted Cajun. As it falls through the atmosphere, its drag is measured by means of an internal accelerometer (see Fig. 3).

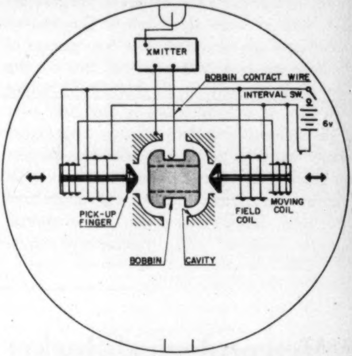


Fig. 3. *Diagram of Accelerometer in 7-inch Sphere. When the sphere is in free fall, the bobbin floats in the cavity. Drag acceleration causes the bobbin to move to the wall. The bobbin is centered and released by the pick-up fingers.*

Atmospheric density is calculated from the equation:

$$\text{drag} = \tfrac{1}{2} D v^2 C_D A,$$

where

D = density of air
v = velocity of sphere
C_D = drag coefficient
A = cross-sectional area

The drag coefficients are known from scaled wind-tunnel tests at low pressures. Velocity is obtained by timing the free-fall from peak altitude of the rocket. It is therefore possible, with the measurement of deceleration, to calculate D.

The altitudes for which the experiment is effective depend on the height from which the sphere is dropped, the ratio of the sphere's area to its mass, and the sensitivity of the accelerometer. The equipment now in use yields data for altitudes between 10 and 90 km. The accuracy is within 10% of the true value throughout this altitude range; its primary limitation is uncertainty regarding the values of the drag coefficients. Pressures and temperatures may be derived from the computed densities.

Results: Data are not yet available from the three falling-sphere experiments launched from Fort Churchill during the IGY. However, in a series of five Nike-Cajun launchings in the North Atlantic in November 1956 as part of the pre-IGY test program, density measurements were obtained up to 80 km at three latitudes. One initial conclusion is that in this region of the atmosphere the density values are less in high latitudes than in lower latitudes.

These sphere samplings, taken at latitudes of 49°, 58°, and 66°N, when compared with sphere data from Wallops Island (38°N) and White Sands (32°N) suggest that air densities at 50 km vary markedly with latitude, decreasing about 2% per degree of latitude.

The Rocket-Grenade Experiment

Technique: The rocket-grenade experiments at Fort Churchill were conducted jointly by an Army Signal Corps group under W. G. Stroud and a University of Michigan group under L. M. Jones. In this experiment, the temperatures and winds of the upper atmosphere are measured by means of explosions of charges carried aloft and ejected from Aerobees. The positions and times of the explosions in space and the times and angles of arrival of the successive sound waves at the ground are recorded by an array of microphones (see Figs. 2 and 4).

The average temperatures in the levels between grenade explosions are calculated from the relationship:

$$C = \sqrt{\frac{\delta RT}{M}} = K(T)^{1/2},$$

where

C = the velocity of sound in the layer
δ = ratio of specific heats of air
R = gas constant
T = temperature
M = average molecular weight of air
K = constant over the altitude range

The average wind speeds and directions in the air levels between grenade explosions are determined by measuring the differences between the *true* positions of the explosions (obtained by DOVAP) and their *apparent* positions as given by the angles of arrival of the sound waves at the ground. Using this method, the measured temperatures are accurate to ±5°C and the winds to ±10 m/sec in velocity and ±18° in azimuth.

Results: The ten planned Aerobee-Grenade firings of the Churchill program have been successfully completed. Five winter firings and five summer firings were made. Some were in the daytime, some at night; on January 27, 1958, firings were made at midnight and at noon to measure the day's variation of temperatures and winds up to 90 km.

The reduction of the grenade data involves the determination of the positions of each of the grenade explosions from the DOVAP records and the calculation of the angles of arrival of the sound waves. The calculation of the temperature and winds from these elements has been programmed on an IBM 650 computer, which speeds up the final steps of the reduction. However, the DOVAP reduction for positions is done

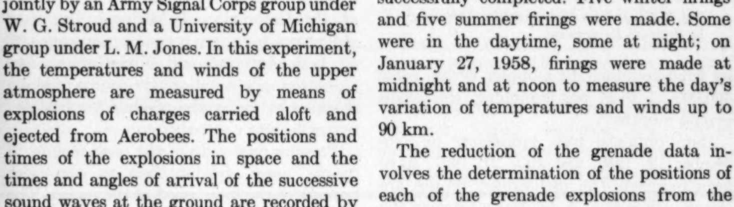


Fig. 4. *Rocket Used in Grenade Experiment*

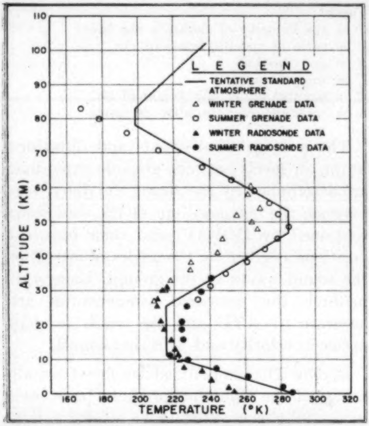


Fig. 5. *Upper Air Temperatures Measured by Grenade Experiment.*

by hand-counting the Doppler cycles, some 400,000 of them per launching; this takes several months.

Data obtained from launchings on November 12, 1956, and July 21, 1957, have been reduced. The preliminary results are shown in Figure 5. A difference between the summer and winter temperature distributions throughout the entire altitude region is shown. At 50 km, the spread is about 20°C; this is a significant amount. The winter measurement is characterized by low temperatures below 50 km and a broad, sporadic distribution from level to level. The summer sounding is, by contrast, quite smooth. It progresses to an extremely low temperature at 80 kms, 165°K (−108°C). This is the lowest temperature ever measured in the atmosphere.

The temperature data obtained from radiosondes flown at the times of the rocket soundings are also plotted in Figure 5. The soundings overlap in the 30-km altitude region and the data match quite well.

The winds measured in the grenade experiment have the characteristic summer-winter difference observed in lower latitude measurements. The winds are weak and from the east in the summer, very strong and from the west in the winter. A west wind of 150 m/sec (335 mph) was observed at a height of 58 km on November 12, 1956.

An additional finding of the Churchill launchings is the fact that above about 90 km the grenade experiment does not work. Even with four-pound explosives, sufficient energy cannot be transferred to the atmosphere to permit sound arrivals at the ground.

The Aerodynamic Experiment

Technique: In the aerodynamic experiment, a gauge mounted at the tip of the nose cone of the rocket measures stagnation, or ram, pressure. Other gauges measure pressure at the sides of the cone. N. Spencer of the University of Michigan has used alphatrons for these pressure measurements on both Aerobees and Nike-Cajuns. The alphatron uses a radioactive source of alpha particles to ionize the residual air between two collecting electrodes.

Pressure at the tip of the nose cone is, of course, much greater than on the sides because of the high speed of the rocket. The ratio of these two pressures is theoretically related to the Mach number, the ratio of the speed of the rocket to the speed of sound in the surrounding atmosphere. As the velocity of sound increases with temperature, the experiment therefore makes it possible to calculate atmospheric temperatures. The results are valid up to about 100 kms.

Results: As do all other experiments except the sphere experiment, the aerodynamic method needs detailed trajectory data before the pressure measurements can be used in evaluating other physical properties of the atmosphere.

Preliminary data from the six aerodynamic experiments indicate that between altitudes of 20 and 80 km in the Arctic, densities are 2–3 times lower than those measured previously at lower latitudes.

Gauge Experiments

Techniques: H. La Gow and his colleagues at the Naval Research Laboratory have applied earlier NRL work to measurements in the Arctic using Aerobee-Hi rockets. These measurements of pressure and density (from which temperature may be derived) are carried out as follows: Pressure gauges of various pressure ranges are scattered over the surface of the rocket, measuring stagnation and cone pressures, and pressures elsewhere on the rocket. The gauges measure pressures from 760 mm Hg to 10^{-6} mm Hg.

Roll modulation, or the change in amplitude of the gauge output with roll of the rocket, appearing on the side-cone gauges also permits the determination of the atmospheric pressure at higher altitudes (10^{-7} mm). These Aerobees are sealed throughout to prevent interior gases from leaking out. This permits an accuracy of measurement approaching the limits of sensitivity of the gauges.

This multiple-gauge approach has made possible measurements to much higher altitudes than the other techniques. Its accuracies, as given by NRL, are:

	Altitude	Error
Pressure data	25–80 km	5–15%
	110–150 km	20–50%
Density data	30–80 km	2–10%
	110–300 km	20–200%

Results: Since the accurate trajectory data required for complete analysis of the properties measured is not yet available, the reduction of data from the gauge experiments is incomplete and preliminary; however, three successful firings have been carried out at Churchill. As found in the falling sphere experiment, the densities measured are lower than those previously measured at White Sands. This seems to be true up to about 200 km. However, the measurements suggest that above this altitude summer day densities are 20 times higher than those of winter night, and winter day densities are 10 times higher than those of winter night.

Other Methods

Two other methods for measuring atmospheric density at rocket altitudes should be mentioned. Mass spectrometers for determination of gas and ion composition have obtained density data. Also, it has been observed in the grenade experiment that at the time of each explosion a period disturbance appears on the DOVAP-cycle record. This disturbance is apparently a measure of the velocity of the shock wave from the explosion. Since this is a function of air density, it becomes possible to determine the density at each grenade altitude. F. L. Bartman of the University of Michigan is at present working out this technique.

Time Variations: A specific problem in the comparison of the rocket data is that of time variations. Simultaneous measurements during the different experiments, although highly desirable, are difficult because of the limited space on the vehicles and the limited facilities for launching and tracking on range. However, at noon on January 27, 1958, an Aerobee carrying both the rocket-grenade experiment and a small sphere was launched. Twenty-nine minutes later a Nike-Cajun carrying the aerodynamic experiment was successfully launched. A comparison of the results from these three techniques will be particularly interesting and valid.

USSR Methods

The USSR is also conducting Arctic rocket-sounding programs during the IGY, using a meteorological sounding rocket to measure temperatures and pressures up to about 110 km. The USSR-IGY Committee has reported that between November 1957 and March 1958 six rockets were launched in Franz Joseph Land.

As described in Soviet literature, the

instrumentation consists of thermal and membrane manometers for measuring pressure, and an electric resistance thermometer for temperatures. An interesting feature of this technique is the use of a parachute throughout the entire downward leg of the trajectory to orient and slow the separated instrumentation section in its fall.

Previously published USSR results for the upper middle latitudes show general agreement with US-IGY results in this field.

It is still too early in the data analysis phase of IGY to draw broad conclusions. However, the prospect of obtaining meteorological data up to an altitude of 250 km at various sites throughout the world is excellent.

Ross Ice Shelf Deformation Project: 1957–58

This report is based on material furnished by James H. Zumberge, University of Michigan, Chief Glaciologist of the Ross Ice Shelf Deformation Project.

Along the margin of the Antarctic Continent are several ice shelves, thick ice formations with level surfaces, extending seaward from the land to which they are attached. One of these is the Ross Ice Shelf, the largest ice shelf in the world, extending about 500 miles in an east-west direction and 400 miles north-south.

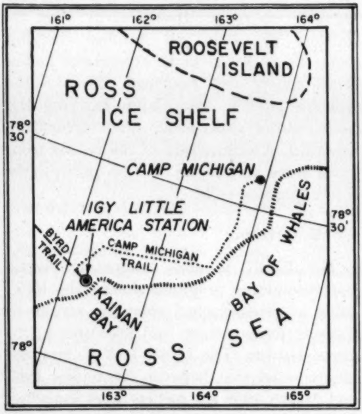


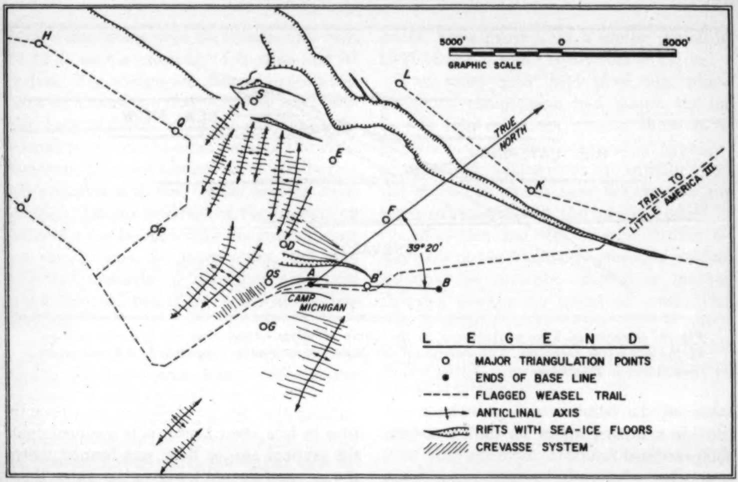
Fig. 6. *Location of Ross Ice Shelf Deformation Project, 1957–1958.*

The IGY Ice Shelf Deformation Project is concerned mainly with the measurement and mapping of deformed ice features of the Ross Ice Shelf between Roosevelt Island and the Bay of Whales. The deformation of shelf ice appears to involve some mechanism of plastic flow. If this mechanism can be determined for ice, it is possible that the results may be applicable to larger structures of the earth's crust, such as the folded Appalachians.

Camp Michigan, the base for these studies, was established on November 20, 1957, at 163°57.3′W, 78°34.0′S (see Fig. 6). The camp site is in the heart of a disturbed-ice area located by use of aircraft based at Little America Station, about 37 miles to the northeast.

During the 1957–58 Antarctic summer, Camp Michigan was supported by helicopter from IGY Little America Station. The camp itself was established by moving equipment and supplies from Little America with a 20-ton, tractor-drawn sled over a trail established November 12–15, 1957.

Scientific personnel consisted of a chief glaciologist, two assistant glaciologists, and a surveyor-photographer. A geophysical team spent approximately 10 days in the area taking seismological soundings and gravity measurements. Other temporary personnel included a Navy photographer and a Navy electronics technician.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CAMP MICHIGAN
TRUE NORTH
TRAIL TO LITTLE AMERICA III
39°20'
LEGEND
○ MAJOR TRIANGULATION POINTS
● ENDS OF BASE LINE
FLAGGED WEASEL TRAIL
ANTICLINAL AXIS
RIFTS WITH SEA-ICE FLOORS
CREVASSE SYSTEM

Fig. 7. *Preliminary Map of Major Structural Features of the Ross Ice Shelf Near Camp Michigan, Antarctica.*

Triangulation and Mapping

The first phase of the study involved the establishment of a base line and triangulation network. Seventeen stations in an area of approximately 25 square miles were located and surveyed. Vertical aerial photographs were taken from an altitude of 5000 ft with a 6-inch camera. The photos overlapped sufficiently for stereographic (three-dimensional) study and radial-line plots for the establishment of a network of points on the ice surface whose positions and distances with respect to one another are accurately known.

Large-scale topographic maps were made of selected areas (see Fig. 7). This will permit details of change in the shelf-ice surface to be recognized in subsequent years.

Deformational Features

Three types of deformational features were recognized: (1) anticlines (elongated upward folds) produced in the shelf ice by horizontal compression; (2) transverse crevasses cutting across the anticlinal axes, produced by horizontal tension; and (3) structures resulting from shearing motions in the ice.

Compressional Features: The anticlines (Fig. 8) are roughly parallel; they are about 15 to 50 ft high, more than 300 ft across, and 2000 to 5000 ft long. As many as four or five nearly parallel anticlines within one square mile are not unusual in this region. Most of the anticlines are symmetrical, but a large one seen from the air was definitely asymmetrical. The similarity of these structural features of the Ross Ice Shelf to folds in sedimentary rocks of the earth's crust is apparent.

Some idea of the rate of the horizontal strain causing the anticlines to form was gained by remeasuring the baseline. The baseline was essentially at right angles to the anticlinal axes. The original length of the baseline was 5800.0 ft; 42 days later it had shortened by 7.6 ft. Another measure-

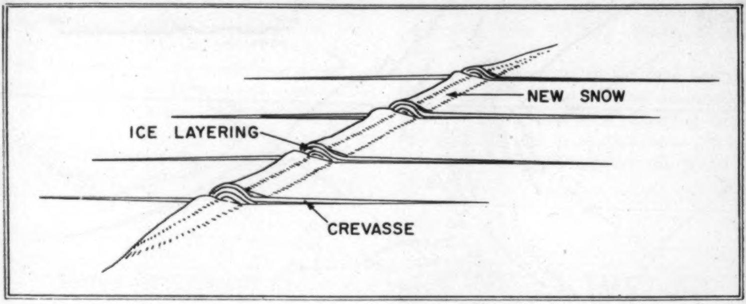

Fig. 8. *Diagram of Typical Anticline in the Camp Michigan Area. Note the layering exposed by the transverse crevasses. The individual ice layers, here greatly exaggerated, are mostly an inch or less in thickness.*

ment of the baseline one year later will provide a further check on the short-term compressional rate.

Tensional Features: Complementary to the compression-formed anticlines are evenly-spaced crevasses that cut across them at right angles to the anticlinal axes (see Fig. 8). These crevasses, produced by tension, range in width from a few inches to more than 100 ft. They are widest where they cross the anticlinal crests. Strain gauges calibrated to thousandths of an inch were installed in some of these crevasses; they showed that the rate of opening was constant, although rates differed from crevasse to crevasse. One small crevasse, 7.38 inches wide, opened 0.47 inches in 19 days. Another crevasse, 7.0 inches wide and 58 ft deep, closed at a constant rate, 0.235 inches in 25 days.

One crevasse not associated with the tensional crevasses was especially interesting because it contained a sea-ice floor 69 ft below the surface of the shelf ice. The sea-ice floor was broken by an 8- to 10-inch rift parallel to the trend of the crevasse itself, which was 41 inches wide at the bottom and about 5 ft wide at the top. The walls of the rift, 25 inches high, consisted of 9 small terraces. The width of the largest terrace was 2 inches.

The presence of the series of small terraces suggests that the ice shelf rose from time to time in this area; hence, it is assumed that the original sea-ice floor was formed when the ice shelf floated lower in the water than it did when the crevasse was examined. One possible explanation for the subsequent gain in buoyancy is that sea water was freezing onto the bottom of the ice shelf in this region. Investigations of similar crevasses that open to sea level will be made in the future to test this hypothesis.

At a depth of 25 inches below the sea-ice floor, free brine was encountered. A specific gravity test of the upper few inches of the sea-ice floor indicated a salinity of 7 ppm (parts/million) sodium chloride. Although the brine was not tested, it must have been highly concentrated since it remained unfrozen despite an atmospheric temperature at the bottom of the crevasse of about −20°C.

The walls of most of the crevasses observed did not contain secondary icing, or formation of ice subsequent to development of the crevasse, a common characteristic of crevasses in more temperate glaciers; for this reason, the walls of the ice-shelf crevasses showed excellent exposures of the ice strata.

Almost every crevasse in the study area is partially or completely covered by a snow bridge. These bridges range in thickness from a few inches over the smaller crevasses to 12 ft over a crevasse 14 ft wide and 80 ft deep. The bridges are difficult to see when light conditions are poor but they are generally easy to detect when the sun is not obscured by clouds. In some areas of the shelf, however, the snow bridges are so thoroughly incorporated into the regular surface snow pattern that no evidence of the underlying crevasses can be seen from the ground, even on sunny days. In these areas, the only effective methods of detection are aerial inspection and use of an electrical crevasse detector.

Shear Features: Shear features in the Camp Michigan area consist of crevasse systems, in echelon patterns, not associated with anticlines. Other shear features are produced late in the developmental history of the anticlines when the strain rate increases to the point where plastic deformation is no longer possible. At that time the arched form of the anticline breaks into irregular blocks. The blocks are often not recognizable from the surface but can be seen by studying aerial photographs.

Snow Stratigraphy

Snow pit studies and examination of crevasse walls were initiated in November and December 1957. A 4-meter pit near Camp Michigan in an undisturbed area revealed a stratigraphic sequence of hard and soft layers representing accumulation back to the summer of 1951. The 1951 layer formed the bottom of the pit. At a depth of 270 to 271 cm from the November 1957 surface, an ice band marks the melting which occurred during the 1952–1953 summer. This melting provided free water that percolated downward through older layers, as evidenced by vertical ice pipes (elongated bodies of clear ice formed by refrozen melt water) below the 270–271 cm ice layer.

Snow accumulation from the end of the 1956 winter to the end of the 1957 winter was 48 cm, with an average density of 0.333. This is equivalent to about 16 cm of water. Accumulation for a similar period in 1955–56 had a water equivalent of 17 cm.

Two more snow pits were dug where horizontal compression had caused the ice to fold into anticlines. One of these snow pits was placed at the bottom of the syncline, or downfold, adjacent to an anticline and the other was placed near the crest of the same structure. Both the strata studied in the snow-pits and the layering visible on the walls of the transverse crevasses cutting through the anticline showed a marked thinning toward the anticlinal crest. This occurs because newly fallen snow is swept from the exposed crest by the wind, whereas accumulation is accentuated in the adjoining synclinal trough.

Comparison of accumulation values for the years 1951–57 in the two pits showed that the synclinal trough received 40% more accumulation than the adjoining anticlinal crest; but the trough received only 5% more accumulation than was measured during the same interval in the first pit, near camp, which represented normal accumulations in the absence of unusual surface obstructions.

The importance of stratigraphic studies in the deformed areas is similar to the importance of stratigraphy in structural geology. In this particular case, it is hoped that the walls of the transverse crevasses will yield a continuous record of snow layers back to a time before the anticlines existed, that is, before the presence of anticlines exerted an influence on the local patterns of snow accumulation. With this information it should be possible to determine the rate of anticlinal growth, or more specifically, the compressional strain rate in the area.

Density Depth Profile: A density-depth profile was made from the surface to the bottom of a 36-meter-deep crevasse. Samples were taken from the walls at intervals of one meter down to a depth of 25 meters; below this, the crevasse was filled with snow from an earlier, collapsed snow bridge, or bridges. By drilling through this material to the bottom of the crevasse, the final density measurement was obtained. The density values comprising this profile, shown in Table 2, are representative for this area.

Table 2. *Density-Depth Values Near Camp Michigan*

Depth (meters)	Density (gm/cm³)
0	0.300
5	0.486
10	0.562
15	0.626
20	0.672
23	0.687
36	0.774

Thermal Studies

Thermohms (temperature sensing devices based on electrical resistance) were buried in the shelf ice at depths of 0.25, 0.50, 1.0, 2.0, 4.0, and 6.0 meters. Readings were taken once a day at 2400 GMT. A sample of the temperatures obtained is given in Table 3.

An additional temperature measurement was made at 24.5 meters below the surface in the wall of a crevasse near the camp. A probing dial thermometer inserted 3 inches into the crevasse wall in late November registered −25.0°C. (The snow bridge above the crevasse collapsed, precluding further measurement.) More temperature records will be made at greater depth during the 1958–59 season.

Meteorological Observations

Measurements were made every three hours (when possible) of temperature, barometric pressure, wind velocity and direction, cloud type, sky cover, and visibility. These records have not been completely analyzed. Generally speaking, however, the weather at Camp Michigan from November 21, 1957, to January 7, 1958, was mild. Temperatures ranged from a low of 5.0°F to a high of 34.5°F during this period. The sky was usually overcast to slightly overcast. Wind velocities ranged from 1 or 2 knots per hour to 25 knots. Winds of 15 to 20 knots were not uncommon in late November and December 1957. Prevailing winds were from the southwest but the strongest winds came from the northwest.

The strong winds and overcast skies caused difficulties in the surveying work with alidade and plane table. Overcast skies also made travel over the crevassed areas unsafe. The poor visibility prevented differentiation between snow-covered crevasses and the non-crevassed snow surface.

Future Program of Study at Camp Michigan

Camp Michigan will be reoccupied during the 1958–59 field season by a four-man team. The program of study inaugurated during the 1957–58 season will be continued and expanded. The work to be done will include the following:

1. Remeasurement of the baseline.
2. Resurvey of selected triangulation stations.
3. Aerial photography of the same area covered during the 1957–58 season.
4. Measurement of snow accumulation stakes placed in December 1957.

Table 3. *Ice Temperatures at Various Depths Near Camp Michigan*

Date	Time (GMT)	Temperature in −C°						
		Surface	.25m	.5m	1 m	2 m	4 m	6 m
24 Nov 57	2400	08.0	13.50	16.10	19.95	23.15	25.75	24.87
30 Nov 57	2400	05.0	12.35	13.85	17.70	22.40	25.60	24.87
4 Dec 57	2400	02.2	7.00	10.63	16.10	21.55	25.15	24.78
10 Dec 57	2400	06.5	9.36	12.02	15.16	20.40	24.76	24.64
14 Dec 57	2400	03.3	6.82	10.56	14.58	19.92	24.56	24.62
19 Dec 56	2400	02.6	5.58	9.26	13.62	19.18	24.16	24.52
23 Dec 57	2400	01.6	4.80	8.78	12.98	18.60	23.86	24.40
27 Dec 57	2400	02.5	4.66	7.86	12.48	18.12	23.60	24.18

5. Re-establishment of latitude and longitude by sun fixes.
6. Petrofabric studies (studies of the patterns produced by crystals) of the ice layers in deformed and undeformed areas.
7. Stratigraphic studies in snow pits and crevasse walls.
8. Further measurements of the rate at which crevasses are opening.
9. More detailed study of snow bridges and bottoms of crevasses.
10. Collection of more thermal data, with emphasis on deeper measurements.
11. Weather observations.

IGY Nuclear Radiation Investigations

The following material was furnished by Lester W. Machta and Robert List of the US Weather Bureau. Dr. Machta is chairman of the Working Group on Nuclear Radiation of the US-IGY Technical Panel on Meteorology.

At the Fourth Session of CSAGI (Special Committee for the IGY), held in Barcelona in September 1956, a recommendation by the Working Group on Nuclear Radiation to measure on a worldwide basis the radioactivity of the air, of precipitation at the earth's surface, and of solid particles deposited on the ground was endorsed.

Following endorsement of this recommendation, the Working Group met in Utrecht in January 1957. Problems related to nuclear radiation in the various fields of geophysics were discussed, and a simple collection and analysis program was formulated. The program includes establishment of a global observational network and preparation of a manual of observational standards and techniques.

The primary aim of nuclear radiation studies during the IGY is to utilize the radioactive "tracers" carried in the atmosphere and oceans to obtain a better understanding of many meteorological and oceanographic phenomena. This report describes portions of the US-IGY program of study of airborne and deposited nuclear radiation.

In addition to the information to be derived from the study of natural radioactivity, study of the artificially produced radioactive products of atomic fission and neutron-induced activities in the atmosphere is yielding much new data. With careful observation and analysis, important light may be obtained on atmospheric circulation, motions, and processes.

In this area are problems related to the identification and movement of air masses; the storage times of minute particles in the troposphere and stratosphere; exchange processes between the stratosphere and troposphere; small- and large-scale diffusion of atmospheric constituents; heat and moisture exchange between the atmosphere and the oceans; features of the large-scale circulation, including stratospheric transport; and the mechanism of precipitation scavenging—the removal of atmospheric particles by rain and snow.

US agencies participating in this program are the Atomic Energy Commission, the Geophysics Research Directorate of the Air Force Cambridge Research Center, the Naval Research Laboratory, the Public Health Service, and the Weather Bureau. In addition, cooperative agreements have been made with various agencies in other countries, especially meteorological services, to assist in sample collection and to participate otherwise in the program. With the exception of the Public Health Service program, most collections in continental United States are made at Weather Bureau stations.

Program of the Atomic Energy Commission

The New York Operations Office of the Atomic Energy Commission has two programs for collecting radioactive fallout. One consists of exposing one-square-foot sheets of gummed cellulose-acetate film on horizontal surfaces about three feet above the ground. Collections are made daily at 39 stations in the continental United States and cooperatively at 81 stations elsewhere in the world. At each station, the film is left exposed for 24 hours, then mailed back to New York. Here, the film is reduced to ash, placed in a plastic planchet and fed through an automatic counting device, where the total beta activity of the sample is determined.

The second program consists of continuously exposing to the atmosphere high-walled, stainless steel pots 0.82 square ft in area. Such pots are in use at 10 stations in continental United States and 16 elsewhere in the world. Each month, the contents of the pots, rinsed with distilled water if necessary, are bottled and shipped to New York for analysis of gross fission products, beta activity, and strontium-90 content. A gradual expansion of the station network is anticipated.

Program of the Public Health Service

The Public Health Service Radiation Surveillance Network, operating cooperatively with the Atomic Energy Commission, consists of 42 field sampling stations and a central laboratory. The central laboratory and three of the field stations are operated by the Public Health Service, the remainder of the stations are under the supervision of the appropriate state or territorial departments of health. Personnel are furnished either by the States or by cooperating local health departments.

Measurement of the concentration of fission products is made by filtering air through a four-inch-diameter dust filter at a rate of about 34 ft^3/min. Two sampling schedules are used: (1) continuous sampling for 24-hour periods, and (2) sampling on a timer-controlled schedule of one hour out of every three over a period of approximately 3½ days. The station operators estimate the activity on a filter and then send it to the laboratory in Washington, D. C., for counting. The filters are measured for beta activity with a thin-window, 7½-inch, gas-flow proportional counter. Each sample is counted at least three days after collection and again seven days later. On the basis of these two activity measurements, and assuming that the beta activity has decayed according to the Way-Wigner formula (radioactive fission products decay at a rate proportional to $t^{-1.2}$, where t = time from the formation of the products), the activity is extrapolated back to the end of collection.

Precipitation samples are collected by 20 of the network stations. When precipitation occurs, one sample is taken during each sampling period. The sample is collected in a bottle using a funnel 0.4 square meters in area. At the collection site, 0.5 liters of the collected precipitation is evaporated to dryness in a rectangular aluminum dish. The dish is then sprayed with plastic, flattened, and mailed to the central laboratory for counting. Activity is extrapolated back to the end of collection in the same manner as with the air filters.

Program of the Naval Research Laboratory

The program of the Naval Research Laboratory is carried out at a network of 20 stations extending along the 80°W meridian from Thule, Greenland, to Punta Arénas, Chile. Daily air-filter collections are made at all stations. In addition, four stations elsewhere are making weekly air-filter collections, and a complete air monitor unit is in operation at IGY Little America Station, in Antarctica. Cooperative agreements with the various participating governments and agencies are in effect.

Each station making daily collections is equipped with a positive-displacement air pump driven by a constant-speed electric motor. This apparatus pumps about 30 ft^3 of air/min through a filter paper 8 inches in diameter. Filters are changed each morning and forwarded to the Naval Research Laboratory in Washington, where they are burned to ash at a temperature of 650°C, and compressed until wafer thin. Counting is done with a thin-window, halogen-filled G.M. tube. Each sample is counted 14 days after collection. Weekly collections are made with a larger filter (17 × 13 inches) having a flow rate of 35 ft^3/min.

Monthly composites of individual samples from each station are being analyzed for the following radioisotopes: Sr^{89}, Sr^{90}, Y^{91}, Cs^{137}, Ce^{141}, Ce^{144}, and Pb^{210}.

The equipment at Little America Station automatically monitors the filter during collection and follows the rate of decay during the next 18 hours. In this way, information is made available on natural radioactivity as well as on fission-product activity.

Program of the Air Force Cambridge Research Center

Six of the stations in the 80°W network of the Naval Research Laboratory program are also participating in the Cambridge Research Center program. At these stations, all of which have appreciable precipitation, the precipitation is collected and sent to a laboratory to be analyzed for Sr^{90}, Pb^{210}, tritium, and other individual radio-isotopes. Measurements of Sr^{90} are made on all samples; only selected samples are used for the other elements. In addition, snow cores and fresh snow from Greenland and the Antarctic are analyzed.

World Warning Agency Decisions

January 1, 1958—June 30, 1958

During the first six months of the IGY, 16 periods of Alerts and 7 SWI (Special World Intervals) were declared by AGIWARN, the IGY World Warning Agency, operated by the National Bureau of Standards at Fort Belvoir, Virginia, near Washington, D. C. (See *Bulletins 5* and *7* for details in this six-month period.)

During the next six-month period 11 Alerts were declared covering a total of 46 days and 6 SWI, covering 16 days, were declared.

Following are the Alerts, SWI, geomagnetic disturbances, and major flares that occurred from January 1, 1958, to June 30, 1958. Alerts and SWI are numbered serially from Alert number 16, which ended on December 29, 1957, and from SWI number 7, which ended on November 27, 1957.

Jan	*8*	*1600*	*Alert #17 starts*
	10	*1600*	*Alert #17 finishes*
Jan	*13*	*1315*	*Class 3 Flare*
	15	*1640*	*Class 3 Flare*
	23	*0904*	*Class 3 Flare*
	25	*0925*	*Class 3 Flare*
		0930	*Class 3 Flare*
		0935	*Class 3 Flare*
		1205	*Class 3 Flare; sudden ionosphere drop-out and gradual recovery*
	27	*1600*	*Alert #18 starts*
	29	*1600*	*Alert #18 finishes*
	31	*1155*	*Class 3 Flare*
Feb	*9*	*1600*	*Alert #19 starts*
	10–11		*Great aurora display, one of the most active periods of the IGY*
	11	*0126*	*Sudden commencement magnetic storm*
		0823	*Class 3 Flare, sudden ionosphere drop-out and gradual recovery*
	13	*15xx*	*Magnetic storm ends*
		1600	*Alert #19 finishes*
	26	*1600*	*Alert #20 starts*
	28	*1600*	*Alert #20 finishes*
Mar	*1*	*0911*	*Class 3+ Flare*
		0912	*Class 3 Flare*
		0916	*Class 3 Flare; sudden iono-*

			sphere drop-out, gradual recovery
Mar	*2*	*1600*	*Alert #21 starts*
	3	*1013*	*Class 3 Flare; sudden ionosphere drop-out, gradual recovery*
	5	*0001*	*SWI #8 starts*
		05xx	*Magnetic storm begins*
	6	*2359*	*SWI #8 finishes*
	7	*111x*	*Class 3 Flare*
		1600	*Alert #21 finishes*
	8	*15xx*	*Magnetic storm ends*
	11	*22xx*	*Magnetic storm begins*
	13	*19xx*	*Magnetic storm ends*
	14	*1212*	*Magnetic storm begins*
		1518	*Class 3 Flare*
		1600	*Alert #22 starts*
	15	*0001*	*SWI #9 starts*
		19xx	*Magnetic storm ends*
		2359	*SWI #9 finishes*
	16	*1600*	*Alert #22 finishes*
	20	*1600*	*Alert #23 starts*
	21	*0001*	*SWI #10 starts*
	23	*0950*	*3 Class 3+ Flares; sudden ionosphere drop-out, gradual recovery*
		0951	*Class 3+ Flare*
		0957	*Class 3+ Flare*
		1005	*Class 3 Flare*
		1009	*Class 3 Flare*
		1540	*Magnetic storm begins*
	25	*2359*	*SWI #10 finishes*
Mar	*27*	*02xx*	*Magnetic storm ends*
	30	*0001*	*SWI #11 starts*
		08xx	*Magnetic storm begins*
	31	*2359*	*SWI #11 finishes*
Apr	*1*	*1600*	*Alert #23 finishes*
	7	*1016*	*Class 3 Flare*
		13xx	*Magnetic storm ends*
		1600	*Alert #24 starts*
	10	*1600*	*Alert #24 finishes*
	17	*00xx*	*Magnetic storm begins*
	19	*00xx*	*Magnetic storm ends*
	30	*1600*	*Alert #25 starts*
May	*1*	*2115*	*Class 3 Flare*
	5	*0906*	*Class 3 Flare*
		1600	*Alert #25 finishes*
	13	*13xx*	*Magnetic storm begins*
	16	*02xx*	*Magnetic storm ends*
Jun	*3*	*1600*	*Alert #26 starts*
	6	*0001*	*SWI #12 starts*
		18xx	*Magnetic storm begins*
	8	*00xx*	*Magnetic storm ends*
		1600	*Alert #26 finishes*
		2359	*SWI #12 finishes*
	19	*0210*	*Class 3 Flare*
		0946	*Class 3 Flare*
		1600	*Alert #27 begins*
	20	*0001*	*SWI #13*
	21	*02xx*	*Magnetic storm starts*
	22	*2359*	*SWI #13 finishes*
	23	*08xx*	*Magnetic storm ends*
		1600	*Alert #27 finishes*
	28	*0713*	*Magnetic storm starts*
	29	*19xx*	*Magnetic storm ends*

IGY World Data Centers and Data Interchange

In accordance with the recommendations of the Third Assembly of CSAGI (Special Committee for IGY) in Brussels in 1955, three World Data Centers were established to maintain collections of IGY data. It was decided that three data centers would insure against the loss or destruction of the data and would serve the geographical convenience of scientists of all nations.

Two IGY National Committees, those of the USA and the USSR, each offered to establish and maintain collections of all the data. These centers were named A and B respectively. A third center, C, is in Western Europe, Japan and Australia. For several disciplines two subcenters of World Data Center C have been established, and are designated C-1 and C-2.

World Data Center A

World Data Center A was established in eleven institutions in eight cities of the United States and Alaska. The U. S. National Committee believes that the interests of science are served best by establishing subcenters for the various disciplines in the institutions which have a history of scientific interest and competence in the appropriate geophysical field rather than by establishing one central archive. The National Academy of Sciences is responsible for the direction of World Data Center A.

The subcenters of World Data Center A are:

(a) *Airglow and Ionospheric Physics:* Central Radio Propagation Laboratory, National Bureau of Standards, Boulder, Colorado. Director: W. B. Chadwick, Chief of Regular Propagation Services Section of Radio Propagation Physics Division of the National Bureau of Standards.

(b) *Aurora (instrumental observations):* Geophysical Institute, University of Alaska, College, Alaska. Director: C. T. Elvey, Head of the Department of Geophysics and Director of the Geophysical Institute of the University of Alaska.

(c) *Aurora (visual observations):* Rockefeller Hall, Cornell University, Ithaca, New York. Director: C. W. Gartlein, Technical Advisor for Physics and Director of the Cornell Study of Aurora.

(d) *Cosmic Rays:* School of Physics, University of Minnesota, Minneapolis, Minnesota. Director: Paul J. Kellogg, Research Associate in the School of Physics, University of Minnesota.

(e) *Geomagnetism, Gravity and Seismology:* U. S. Coast and Geodetic Survey, Geophysics Division, Washington, D. C. Director: J. H. Nelson, Chief, Geomagnetism Branch, U. S. Coast and Geodetic Survey.

(f) *Glaciology:* American Geographical Society, Broadway at 156th Street, New York, New York. Director: William O. Field, Head of the Department of Exploration and Field Research, American Geographical Society.

(g) *Longitude and Latitude:* U. S. Naval Observatory, Washington, D. C. Director: William Markowitz, Director of Time Service, U. S. Naval Observatory.

(h) *Meteorology and Nuclear Radiation:* National Weather Records Center, U. S. Weather Bureau, Asheville, North Carolina. Director: Helmut E. Landsberg, Chief, Climatological Services, U. S. Weather Bureau.

(i) *Oceanography:* Department of Oceanography and Meteorology, Agricultural and Mechanical College of Texas, College Station, Texas. Director: Dale F. Leipper, Head, Department of Oceanography and Meteorology, Agricultural and Mechanical College of Texas.

(j) *Rockets and Satellites:* National Academy of Sciences, Washington, D. C.

(k) *Solar Activity:* High Altitude Observatory, Boulder, Colorado. Director: Walter Orr Roberts, Director, High Altitude Observatory of the University of Colorado.

Current Status of Data Flow

The current status of the flow of data to World Data Center A and of the interchange of data between Center A and the other World Data Centers is set forth below for each subcenter of Data Center A. The second "6-monthly" catalogue of data on hand in World Data Center A was issued on June 10, 1958. It may be noted that the flow of data most nearly approximates the CSAGI schedules in those disciplines in which there was organized international exchange of data prior to the IGY.

To date, World Data Center A has received data from 58 of the 66 nations participating in IGY including all of the larger nations. Data are also being received from stations and nations not formally part of IGY, and some data are being sent for times prior to the commencement of the IGY.

Airglow and Ionospheric Physics: The amount of data received in airglow projects is small at present because processing is laborious. A few months of data have been received from four nations. Some data have been sent to and received from each of the other World Data Centers. Since absolute calibration of IGY airglow photometers has now been completed, data for the first year of observations should reach the data center in the near future.

The flow of ionospheric data is immense. Data have been received from each of the other World Data Centers, and directly from 145 stations in 43 nations. Approximately 320,000 feet (61 miles) of ionogram film have been processed. The dispatch to other Data Centers of data received by Center A is fully current.

To date, fourteen requests for data have been received, and several scientists have already visited Boulder to work with the data on the premises.

In addition to the CSAGI 6-Monthly Catalogue, an interim catalogue of data in Center A for airglow and ionospheric physics was issued in April.

Aurora (instrumental): Data from instrumental auroral studies are flowing more slowly than anticipated. More time has been required to process and reduce all-sky camera films and transmit them to the Data Center than was estimated in the CSAGI schedule. Nevertheless, at present, film has been received from 22 of the all-sky cameras operated by U. S. projects.

Aurora (visual): In the United States there are 424 active volunteer observers from whom 16,000 positive and 50,000 negative reports of auroras have been received. The US Weather Bureau has furnished 20,000 positive and 300,000 negative reports. From these reports, over 1000 auroral maps for 15-minute intervals have been drawn at the Regional Center at Cornell.

Data for the first eight months of IGY have been dispatched to the other World Data Centers. Data have been received from Data Center C. In addition, data have been sent directly to Center A from Argentina, Canada, Cuba, Mexico, and New Zealand.

Cosmic Rays: Data are flowing regularly to Data Center A from Centers B and C. Many stations send data directly to Center A. To date, data have been received at Center A from 21 of the 38 nations participating in the IGY program in cosmic ray studies.

The flow of cosmic ray data during the past five months has been more than five times as great as during the first six months of IGY. Approximately one-third of the stations are up-to-date in their transmittal of data to the centers.

Geomagnetism, Gravity, and Seismology: Magnetic data have been sent to Center A from nations in the Western Hemisphere for forwarding to the other World Data Centers. No data have been received directly from the other World Data Centers; stations which send primarily to these centers send also to Center A, usually through a collecting agency.

Geomagnetic data have been received from 86 stations in 27 of the 49 nations participating in the geomagnetic program. Many requests have been received for geomagnetic data, including requests for the data from the entire chain of variograph stations in the Western Hemisphere.

The flow of gravimetric data has been small as yet. Data sent to World Data Center A include earth tide studies at three stations in Japan and one station in Hungary.

Bulletins containing seismic data have been sent directly to Data Center A from stations or national collection agencies of 22 of the 52 nations which are participating in the IGY program. The bulletins received to date include data from 165 stations.

Glaciology: The flow of data to the subcenter for glaciology has been limited to progress reports from 13 glaciological projects in Canada, New Zealand, and the United States. The basic data for the field work accomplished during the first Antarctic summer, which ended in March of this year, is being compiled and should be transmitted to the Data Centers within the coming four months. This Center has issued the first volume of the World Data Center A Glaciology Report Series. This volume includes preliminary reports received by the Center prior to June 23, 1958.

Longitude and Latitude: Data from the two programs in longitude and latitude are reaching the appropriate primary data centers: astrolabe data to Paris, moon position data to Washington. These data will be reduced and published by the primary data centers. The flow of moon position data began only recently because of delays in starting the observation program.

Meteorology and Nuclear Radiation: Most stations submit data directly to World Data Center C. Data from stations in the Western Hemisphere have been forwarded to Centers B and C as required.

Center A has received data from 35 nations, including microfilm for three months of data from the USSR Data Center. A similar amount of microfilm has been dispatched to the USSR Data Center.

The flow of data to Center A from the stations in the United States and North America alone amounts to 25,000 punched cards per day—for the entire world network of stations the data will require about 100,000 cards per day. These data will be reproduced on Microcards by World Data Center C.

The pattern for the flow of data on nuclear radiation was established several months after the beginning of IGY. Center A has received data on nuclear radiation from eleven nations participating in this program.

Oceanography: Sea level data from ten countries have been sent to Data Center A. Cruise reports have been received from nine nations for 39 ships. Data have been sent to and received from World Data Center B. World Data Center A issued an interim catalogue of data received prior to April 1, 1958.

Rockets and Satellites: The CSAGI Guide outlining the operation of the Data Centers for rockets and satellites was issued in April 1958. Prior to this time, very little data had been received by this Center. Because of the nature of rocket and satellite data results, the agreed-upon timetable allows twelve months after completion of an experiment before data are expected. Data have been received at Data Center A from Denmark, Germany, Japan, South Africa, United Kingdom, United States, and USSR.

In order to make the results of rocket and satellite experiments widely available to interested scientists, Data Center A initiated two series of reports: one for rockets, one for satellites. Five issues of the satellite series and one issue of the rocket series containing preliminary data have been published. Some preliminary and informal reports have been received from the USSR, descriptive of their satellite experiments and early results.

Solar Activity: Data flow very promptly in this discipline. Center A has received data from 24 of the 36 nations participating in the solar activity program. In addition to the telegraphic data, written and tabulated reports are received regularly and promptly. Monthly lists of solar flares are dispatched by the 7th of the following month.

As part of the intermediate publication of data, Center A has published Solar Activity Report Series Numbers 1-3, "Reports of Surges and Active Prominence Regions," for the months of July 1957–March 1958.

Reports

In addition to the reports issued by the individual centers, a General Report Series has been established by World Data Center A. The first volume of this series is "Description of the Antarctic Circulation Observed from April to November 1957 at the IGY Antarctic Weather Central, Little America Station." This report is the work of Vladimir Rastorguev of the USSR and Jose Alvarez of Argentina, who spent one season at Little America.

The second volume of the IGY General Report Series is a preliminary report of the "Downwind Expedition" of the Scripps Institution of Oceanography of the University of California. The third volume includes three preliminary reports on the gravity and seismic programs at the University of Wisconsin.

IGY Bibliographic Notes

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The Geochemistry of Tritium*

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Abstract—The tritium concentration has been determined in precipitation, ocean waters, and ground waters. Although the steady-state tritium 'cycle' has been disturbed by thermonuclear testing, enough analyses of pre-test water have been made to conclude that: (1) the North Atlantic surface water had a natural mean $T:H = 1.0 \times 10^{-18}$ which doubled in 1954 because of the Castle tests, (2) this water mixes down to the seasonal thermocline in one year, (3) the North Atlantic Central Water appears to be 25 years old off the coast of Portugal, (4) measurable tritium was found in three bottom samples in the North Atlantic suggesting a young age for some of that water, (5) the hot waters of the Tecolote Tunnel, California, were from recent (nine months) rains, (6) direct runoff of precipitation from the ground surface to streams was at least three per cent of the total precipitation in the Hudson River basin in 1954, (7) the natural rate of production of tritium is calculated from a budget on the North Atlantic to be 0.75 ± 0.4 H^3 atoms/sec cm^2 of Earth's surface.

Introduction—Tritium (H^3 or T) is constantly being produced by cosmic rays in the upper atmosphere, combining with H and O to form HTO, and then entering the water cycle. It is beta radioactive, with a half-life of 12.262 years [*Jones*, 1955] and is therefore useful for certain global tracer experiments.

The discovery of tritium in natural molecular hydrogen in the atmosphere by *von Faltings* and *Harteck* [1950] led to a search for H^3 in natural waters, subsequently achieved [*Grosse* and others, 1951]. The first extensive survey of tritium in natural waters was made by *Kaufman* and *Libby* [1954]. Subsequent studies have been made by *von Buttlar* and *Libby* [1955], *Begemann* and *Libby* [1957], *Fireman* and *Schwarzer* [1954], and *Brown* and *Grummitt* [1956].

An attempt has been made in this investigation to determine the processes and rates of mixing in the atmosphere and oceans. From this information and a consideration of the tritium cycle, the cosmic-ray production rate of tritium is derived.

Procedure—The analysis of the natural waters for tritium concentration involved electrolytic concentration followed by gas proportional counting of hydrogen gas. With present counting techniques, the limit of detection of the ratio of tritium atoms to total hydrogen atoms is $T:H = 1 \times 10^{-16}$ for hydrogen liberated from a 1.4 ml sample of water. Since many samples fall in the range of 10^{-18}, the tritium in the sample must be concentrated before counting.

Techniques developed by *Brown* and *Daggett* [1935] and *Kaufman* and *Libby* [1954] were used [*Giletti*, 1957]. First the water sample is electrolyzed, thus liberating protium preferentially to tritium. The extent of enrichment is monitored by deuterium analysis. Volume reductions by factors of 100 to 10,000 still leave about one half of the initial moles of tritium in the residual water.

The concentrated water sample is converted to H_2 gas by diffusing the water vapor over granulated CP zinc at 400°C. The reaction is quantitative producing H_2 and ZnO.

The counting procedure was developed at this laboratory. A two-liter copper gas proportional counter is filled to 0.9 atmosphere with the sample H_2 and 0.1 atmosphere of purified tank methane. The methane is used to improve counting characteristics. Backgrounds on the two counters are stable to ±0.3 cpm (the backgrounds are 9.5 and 13.8 cpm respectively). For a detailed description of the analytical procedure, see *Giletti* [1957].

Samples of water containing no tritium (such as water prepared by burning dry natural propane in a closed system with specially dried oxygen) were analyzed and found to have a blank value of $T:H = 0.3 \pm 0.1 \times 10^{-18}$. A careful search for the source of this contamination has suggested condensation of water vapor in the electrolytic cells but the problem is not entirely solved. The blanks were quite consistent, however, so that within the error stated above, the correction is reliable. The blank value is not a function of the extent of electrolytic enrichment. The volume enrichment factors vary at least threefold with no consistent variation in the blank value.

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* Lamont Geological Observatory Contribution No. 292.

TABLE 1—*Tritium concentration of precipitation at Palisades, N. Y.*

Description	Date	T:H × 10^{18}
	1953	
Rain	Oct. 25	13.9
Rain	Oct. 25	17.3
Rain	Oct. 28	5.2
Rain	Oct. 29	9.3
Rain	Oct. 30	4.6
Rain	Nov. 24	7.1
Rain	Nov. 25	7.5
Rain	Nov. 25	8.5
Rain	Dec. 29	13.1
	1954	
Snow	Jan. 11	5.6
Snow	Jan. 20	4.1
Snow	Feb. 16	13.0
Rain	Mar. 3	4.9
Rain	Mar. 3	5.6
Rain	Mar. 14	1240
Rain	Mar. 19	255
Rain	Mar. 25	243
Rain	Apr. 16	302
Rain	Apr. 17	430
Rain	Apr. 17-18	294
Rain	Apr. 23	59.5
Rain	Apr. 24	110
Rain	May 3	120
Rain	May 9	640
Rain	May 11	458
Rain	May 22	1178
Rain	June 1	204
Rain	June 23	159
Rain	June 25	306
Rain	June 30	150
Rain	July 6	154
Rain	Aug. 3	71
Rain	Aug. 9	46.4
Rain	Aug. 10	81
Rain	Aug. 20	51.2
Rain	Aug. 31	16.4
Rain	Sept. 8	55.6
Rain	Sept. 16	24.0
Rain	Sept. 16	31.2
Rain	Sept. 20	22.9
Rain	Sept. 21	30.0
Rain	Sept. 30	11.4
Rain	Oct. 6	39.3
Rain	Oct. 30	13.1
Rain	Nov. 2	43.5
Rain	Nov. 2	7.1
Rain	Nov. 6	20.1
Rain	Nov. 7	9.0
Rain	Nov. 24	19.7
Rain	Dec. 9	13.5
Rain	Dec. 17	15.4
Rain	Dec. 19	2.9
Rain	Dec. 29	6.9
	1955	
Snow	Feb. 7	18.9
Rain	Feb. 11	6.2
Rain	Feb. 21	37.5
Rain	Mar. 16	37.2
Rain	Mar. 18	12.3
Snow and Rain	Mar. 26	16.7
Rain	Apr. 12	23.2
Rain	Apr. 26	17.8
Rain	July 24	33.2

RESULTS

The results are presented in units of T:H × 10^{18}. These concentrations have had the blank value of T:H = 0.3 × 10^{-18} subtracted from them and have been corrected for the decay of tritium between the times of collection and counting. For all values of T:H > 1 × 10^{-18}, the error is a 1 σ of 10 pct. The blank correction error dominates in the lower concentrations. Tables 1–5 list the results obtained at this laboratory grouped into suitable categories. The Lamont precipitation data are listed chronologically (Table 1), the European results are listed in a north to south direction (Table 3) and the Atlantic subsurface data are listed as a function of depth (Table 5).

METEOROLOGICAL OBSERVATIONS

Analyses of rains and moisture for tritium and some correlation with meteorological data were performed by *Kaufman* and *Libby* [1954], *Fireman* and *Schwarzer* [1954], *von Buttlar* and *Libby* [1955], *Brown* and *Grummitt* [1956], and *Begemann* and *Libby* [1957]. The analysis of rains at Lamont began in the fall of 1953 (Table 1). The overall results are in good agreement with those of the University of Chicago workers. Figure 1 shows the data of both laboratories for a two year period. The logarithmic scale tends to minimize the variations. The early results yield a mean value of 8.4 × 10^{-18} and are considered the natural tritium level if cosmic-ray production only is involved.

Following the explosion of the first thermonuclear device significant to this study, in March 1954, as part of a spring test series in the Pacific, very high and highly variable results were observed until early June of that year (Fig. 1). As a result of the high temperatures at the explosion site, most of the T atoms produced would probably

Table 2 – *Miscellaneous samples from North America*

Description	Date collected	T:H × 10^{18}
Rain		
Atlantic Ocean, 38°26′N, 47° 07′ W	July 4, 1953	3.5 3.3
Bahama Islands	June 1, 1955	6.7
Ground waters		
Monroe Pond, New York City, water supply watershed	Feb. 6, 1954	7.1
Tap water, New York City	Apr. 10, 1954	27.8
Hudson River, Palisades, New York	Mar. 30, 1954	28.8
Lake Mead, Nevada	July 5, 1954	25.0
Mammoth Hot Springs, Yellowstone Park, Wyo.	July 28, 1954	0.8
Small stream, Medicine Bow, Range, Wyo.	July 24, 1954	262
St. Lawrence River	May 27, 1955	11.9
Connecticut River, Hartford, Conn.	Aug. 4, 1955	43.7
Connecticut River, Hartford, Conn.	Aug. 15, 1955	40.0
Tecolote Tunnel, Santa Barbara, Calif.	Jan. 30, 1955	16.2
Tecolote Tunnel, Santa Barbara, Calif.	Jan. 30, 1955	75.1

Table 3 – *European rains and ground waters, 1954*

Description	Date collected	T:H × 10^{18}
Small lake, Hammerfest, Norway	Aug. 5	31.0
Small stream, Hammerfest, Norway	Aug. 5	24.2
Stream, Oslo, Norway	Aug. 9	17.3
Rain, Oslo, Norway	Aug. 9	16.6
Rain, Flensburg, Germany	Aug. 11	15.8
Elbe River, Hamburg, Germany	Aug. 12	20.5
Tap water, Bremen, Germany	Aug. 13	10.8
Weser River, Germany	Aug. 13	9.9
Rhine River, Koln, Germany	Aug. 14	17.2
Rain, Euskirchen, Germany	Aug. 14	22.5
Mosel River, Trier, France	Aug. 15	32.6
Meuse River, Verdun, France	Aug. 15	14.3
Lake Vincennes, Paris, France	Aug. 16	27.1
Loire River, Briare, France	Aug. 18	22.0
Dordogne River, Libourne, France	Aug. 19	24.5
Garonne River, Bordeaux, France	Aug. 20	40.3
Adour River, Bayonne, France	Aug. 21	20.8
Manzanares River, Madrid, Spain	Aug. 24	57.2
Tap water, Madrid, Spain	Aug. 24	48.6

Table 4 – *Tritium concentration of Atlantic Ocean surface waters*

Lat. N	Long. W	Date collected	T:H × ^{18}
° ′	° ′	1953	
40 10	71 10 W	July 22	0.62
43 08	58 46 W	July 24	1.11
40 05	55 00 W	Aug. 1	1.39
43 28	51 05 W	Aug. 9	0.89
48 51	50 10 W	Aug. 24	0.62
34 00	52 35 W	Sept. 7	0.92
34 00	62 50 W	Sept. 10	1.34
37 15	68 00 W	Sept. 11	1.5 ± .4
39 20	71 30 W	Sept. 12	1.31
		1954	
39 05	70 45 W	July 10	4.45
37 18	51 00 W	July 19	1.73
37 18	32 07 W	July 28	1.79
35 04	12 57 W	Aug. 6	1.14
70 55	23 10 E	Aug. 6	1.04
34 57	21 47 W	Sept. 4	1.55
31 58	40 48 W	Sept. 9	1.01
31 31	48 25 W	Sept. 11	1.30
		1955	
34 39.5	52 41.5 W	July 21	1.26
25 05	72 02 W	July 15	2.30
25 15	77 34 W	July 5	1.74

Table 5 – *Tritium concentrations of sub-surface Atlantic Ocean waters*

Date collected	Lat N	Long W	Depth	T:H × 10^{18}	Water type
	° ′	° ′	m		
Mean of eight samples in 1953			0	1.0	Surface water
Mean of eight samples in 1954			0	1.9	Surface water
July 30, 1953	42 28	55 00	46	0.64	Surface water
July 30, 1953	42 28	55 00	91	0.74	Surface water
July 15, 1955	25 04	70 02	46	2.24	Surface water
July 21, 1955	34 41	52 43	60	0.30 ± .1	NACW
Sept. 1, 1954	36 51	14 00	183	0.22 ± .1	NACW
July 23, 1954	38 20	42 50	1830	−0.02 ± .1	NADW
Aug. 31, 1954	37 13	12 17	3660	0.02 ± .1	NADW
Sept. 3 1954	35 22	20 10	3660	0.03 ± .1	NADW
July 19, 1954	37 20	50 59	4340	0.2 ± .1	Bottom sample, NADW
Aug. 30, 1954	37 50	11 26	4900	0.48 ± .1	Bottom sample, NADW
July 24, 1955	37 29	54 55	5160	0.4 ± .1	Bottom sample, NADW

burn rapidly to form HTO and become a part of the moisture content of the air. It is possible, therefore, to calculate the time of washout of the moisture into the Earth and oceans by following the 'decay' of the tritium concentration in rain. Figure 2 shows the pertinent portion of the data. The figure gives all Lamont tritium data in this period. This half-life of retention in the atmosphere was calculated by a least-squares fit to the data to be 35 days. This agrees well with data of *von Buttlar* and *Libby* [1955] and *Brown* and *Grummitt* [1956] but must be regarded as a maximum value since more than one pulse may have been involved.

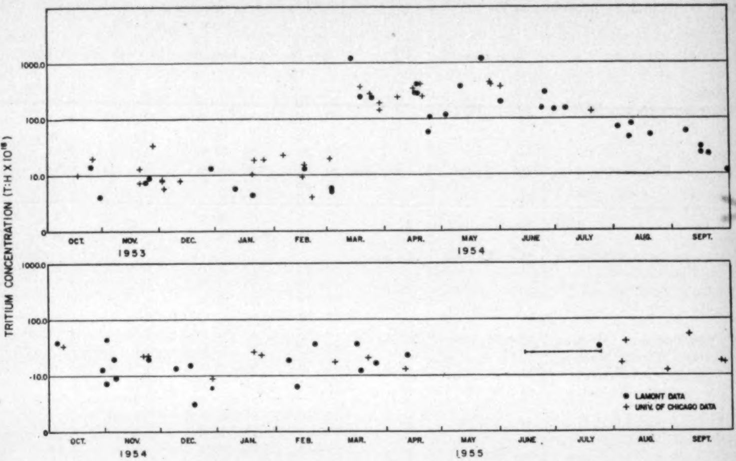

FIG. 1 – Tritium concentration in precipitation from 1953 to 1955

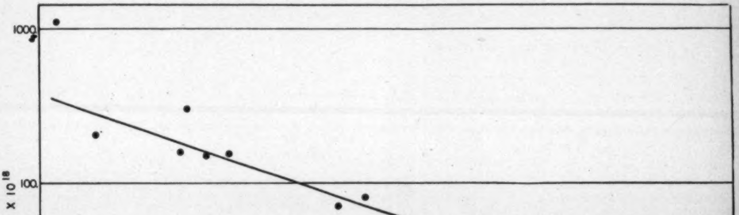

FIG. 2 – Tritium concentration of Lamont rains immediately following the Castle tests 1954; the line is a least-squares fit and gives a $t_{\frac{1}{2}}$ = 35 days

The period following the 'decay' of this atmospheric activity begins at about the beginning of October 1954. During this time a relatively constant T:H is found which is comparable to that for 1953. However, the concentration averages 18.4 (or an increment of 10 over the earlier period). With the rapid washout time this new level must reflect either a large stratospheric reservoir from the Castle and later tests or continuous introduction of tritiated water at ground level from other sources.

Atomic test effect on precipitation—During the period under observation numerous tests were made of atomic devices. It is important to establish the extent that such tests could affect the 1953 data. All subsequent calculations on natural tritium levels of activity are based on the 1953 assay.

The United States conducted two major series of tests during the period under discussion. These occurred in November 1952 and in the spring of 1953. The 1952 tests included the first thermonuclear test explosion. This might be expected to yield tritium concentrations similar to 1954. *Kaufman* and *Libby* [1954] found no such values. The maximum in their data was 66 (as compared to this laboratory's 1240 in 1954). Thus the maximum increment was 4.4 pct of that during the 1954 Castle tests. These authors also obtained the following data:

Sample date	$T:H \times 10^{18}$
Nov. 18, 1952	66 ± 1.0
Nov. 22–25, 1952	19.3 ± 1.5
Dec. 2, 1952	13.2 ± 1.2
Jan. 6, 1953	7.1 ± 0.5

This may be a 'decay' curve or it may represent random variations. At any rate, no extended period of high values such as Mar.–June 1954 occurred. The decay, if any, started immediately. Hence the total increment of tritium (as opposed to the comparison of peak values) must be considered as less than two per cent of that in 1954.

The major increment to the oceans caused by the Castle tests had occurred by the late summer of 1954 (see below) as a result of the large tropospheric fallout. The long-range fallout from the stratosphere added a maximum increment of T:H = 10 for rains at Lamont. Assuming that the increment to 1953 was 8 (that is, the total T:H of the rains) then this would not have been enough to supply the oceans with the tritium observed. However, some increment less than the full T:H = 8 is all that can be assumed. This would affect the oceans by less than two per cent. Thus the 1952 test could not have changed the Atlantic Ocean value and hence the world reservoir estimate, by more than four per cent.

A further question as to the 1953 assay of world tritium arises in connection with the more conventional atomic fission tests. Since a considerable neutron flux is produced, n, t reactions on nitrogen might produce significant tritium. The United States conducted a series of tests in Nevada during the spring of 1953. The data of *Kaufman* and *Libby* [1954] for the spring and summer of 1953 are monotonously constant at about $T:H = 6 \times 10^{-18}$ suggesting no effect from A tests.

Rains at the Brookhaven National Laboratory showed some high tritium contents in 1953 [*Fireman* and *Schwarzer*, 1954]. Two of these rains had T:H ratios of 300 and 800 respectively. There are isolated cases, however, one appearing in August well after the United States tests were over. It is suggested that those rains either reflect the recycling of local laboratory tritium waste from Brookhaven or possibly contamination of the sample. It is concluded that the fission tests are not significant tritium producers.

Geographical tritium variations—The rain study was extended to Europe in 1954. The samples were taken on a traverse from Hammerfest in northern Norway to Madrid, Spain. These data (Table 3) indicate that for comparable latitudes (New York and Spain) the tritium concentrations in surface waters and rain in the latter part of August 1954 were similar. The values decrease somewhat northward probably reflecting the path of the thermonuclear cloud.

The ten northernmost samples average 18.9 while the others to the south (nine samples) average 32.2.

The variations observed in the T:H before March 1954 were presumably of natural origin. A comparison of the T:H ratio to the amount of

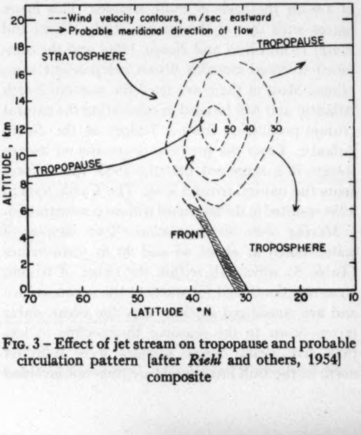

FIG. 3 – Effect of jet stream on tropopause and probable circulation pattern [after *Riehl* and others, 1954] composite

precipitation showed that while considerable variability exists in storms with less than one inch of rain, those with more rain have a T:H < 6×10^{-18}. Thus it is only in cases of extreme dilution that the T:H is significantly affected.

It is suggested that the reason for the variable tritium concentration is jet-stream activity [*Milic*, 1956; *Machta*, 1957]. It is generally accepted that a low-pressure area is often associated with a jet stream at higher altitudes [*Riehl* and others, 1954]. A composite section (Figure 3) illustrates the relationship to the upper air circulation. It was suggested by *Riehl* and others [1954] that air is transferred across the jet stream as shown by the arrows. The higher tritium concentrations in the stratosphere could then affect the T:H in rain in varying degrees.

OCEANOGRAPHY

Tritium enters the oceans from rainfall and exchange at the surface. The value of tritium as a tracer of water masses depends on the definition of the T:H ratio in the surface ocean water. The most obvious application is to the mixing rate of the surface layer. If the rates are fast enough the tritium tracer can also be used to follow the mixing of surface with deeper water.

A survey of North Atlantic surface water was begun in 1953 and is continuing (Table 4). The mean value for 1953 was 1.0×10^{-18} but by 1954 it had risen to 1.9×10^{-18}. Although *von Buttlar* and *Libby* [1955] reported a value of 0.58 for the 1953 North Atlantic surface water, a recent report by *Begemann* and *Libby* [1957] gives the average of 1.0 on the basis of more samples. This figure agrees with that of the present study [*Giletti* and *Kulp*, 1956; *Giletti* and *Bazan*, 1956] and the combined average includes fifteen independent samplings. Most of these are from the western North Atlantic and will be used in calculating the natural tritium production from a budget of the North Atlantic. From the previous discussion on meteorology, it is suggested that the 1953 value represents the natural trituim level. The Castle tests in 1954 resulted in the increased tritium concentration.

Mixing above the thermocline—Two samples of water taken at about 45 and 90 m yield values (Table 5) which fall within the range of tritium concentration found for water at the ocean surface and are considered to show that the ocean water mixes down to the seasonal thermocline in less than five years. These samples were collected north of the Gulf Stream and are thus not involved in the formation of the North Atlantic Central Water. A sample of surface water taken on July 15, 1955 (Table 5) showed the thermonuclear effect of the previous year at a depth of 46 m. It is concluded that the assumptions based on temperature and salinity data of vertical mixing of the surface layer (that is, upper 50 m) within one or two years are confirmed.

North Atlantic Central Water—Two samples of North Atlantic Central Water (NACW) were measured, September 19, 1954 and July 19, 1955, giving values of 0.22 and 0.30 respectively. If the water were flowing in a closed pipe with the surface of the ocean the origin, the age would be about 25 yr. The mean flow rate from the convergence area to the eastern Atlantic at the location of the 1954 sample (36°51′N, 14°00′W) would be ~0.4 cm per sec.

If lateral or vertical mixing were taking place, the water would be a mixture of 25 pct surface and 75 pct old deep water (at least 50 years old). Other combinations are possible as well as a combination of mixing with some direct flow. Since the NACW increases in density with depth, it is possible that lateral mixing or mass flow are occurring at different rates in any given section. Very closely spaced samples in vertical profiles at a number of selected locations would be needed to determine this mechanism. The tritium in the upper portions of the NACW, however, may indicate measurable tritium throughout the mass, although perhaps in lower concentration. If the T:H were 0.2×10^{-18} throughout the Central Water, the calculations on the production rate of tritium would have to be revised significantly (perhaps tripled). Thus it is unlikely that a T:H > 0.1 will be found for the average NACW.

North Atlantic Deep Water (*NADW*)—This water has been found by its natural radiocarbon concentration to have a mean age of 600 yr [*Broecker*, 1957] and is considered to have a T:H < 0.01. The values obtained were $-0.02 \pm .1$, $+0.02 \pm .1$, $+0.03 \pm .1$ (Table 5) all in the usual T:H $\times 10^{-18}$ units. The NADW is thus certainly less than 0.05×10^{-18}. These were samples collected at 1830 and 3660 m depth.

Bottom samples—Three samples were analyzed which come from 40 m above the ocean bottom. These had T:H values of 0.2, 0.48, and 0.40 (Table 5). These results if not caused by contamination suggest that some water which originates in high latitudes at the surface moves rapidly along the bottom to 37°N. If this is true a latitude effect might be observed in the bottom water. The density gradient above the bottom water is small so that upward mixing is possible. Thus the tritium in the bottom water would tend to become diluted with the overlying 'dead' water as it proceeded southward.

The transfer mechanism might be either by direct flow or eddy transfer. The major process would have to involve mixing with the Deep Water alone rather than an age effect since C^{14} measurements do not show markedly different values between the core of the NADW and the bottom water.

It can be concluded that tritium measurements on some of the Atlantic waters are not only possible but useful. Further study in the surface waters and Central Waters should be particularly fruitful, and the bottom water offers intriguing possibilities. A distinct change in T:H is observed between the surface waters and the NACW. This supports the conclusions from the standard T-S analysis that the two water masses do not mix extensively.

HYDROLOGY

Continental surface waters—The response of surface waters to the increased tritium in rains is rapid but varied. The New York City water supply consists of a system of reservoirs north of the city in the Manhattan Prong and the Catskill Mountains. A sample from one of the reservoirs (Monroe Pond) gave a $T:H = 7.4 \times 10^{-18}$ (Table 2) February 6, 1954. *Von Buttlar* and *Libby* [1956] list two other reservoirs at 7.2 and 8.4 so a mean $T:H = 8$ will be assumed. This coincides with the mean tritium content of pre-Castle New York rains, as might be expected from rather small lakes which may turn over in only a few years. All of these samples were collected on February 6, 1954. The first 'hot' rain occurred on March 14, 1954, and the tap water in New York City on April 10 was already up to 28 (Table 2). The Hudson River also showed a marked increase by March 30 with a $T:H = 29$.

Hudson River runoff—The Hudson River sample was taken at an opportune time to measure the amount of water which enters the stream directly. The river is supplied both by surface runoff and ground water. If precipitation enters the ground in the watershed area, it will tend to force other waters to leave the ground and enter the stream. On the other hand, some of the precipitation will enter the stream directly. These two sources combine and the waters in the stream can only be studied as an integrated whole. From the point of view of erosional effects, however, the surface flow is important.

Since the Hudson was sampled shortly after the first significant thermonuclear tests, the rainwater entering the ground was distinctly different from that already in the water table. Specifically, it had a T:H at least thirty times that of the ground water. This, then, provided a means for distinguishing surface from ground water.

The amount of rain which fell in March 1954 was used in this calculation. Four rain periods

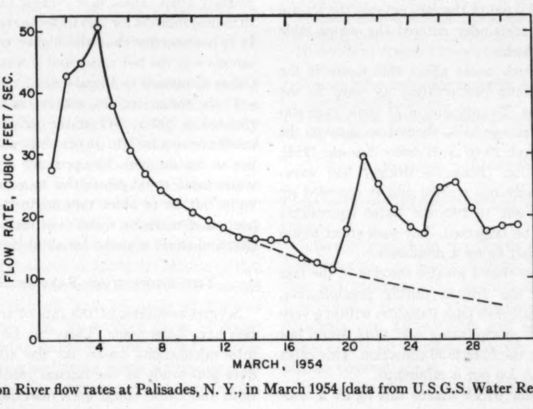

FIG. 4 – Hudson River flow rates at Palisades, N. Y., in March 1954 [data from U.S.G.S. Water Resources Branch]

TABLE 6 – *Data on Hudson Watershed precipitation and tritium content*

Rain	March, 1954	T:H × 10^{18}	Precipitation
			cm
1	13–15	1240	1.28
2	19–20	255	2.09
3	25–26	243	1.35

occurred following the uncontaminated March 3 precipitation and preceding the river sampling. The last of these coincided with the collection and will be neglected. Twenty-three stations were used to derive the precipitation data for the drainage area (U.S. Weather Bureau, 1954). The pertinent information is shown in Table 6 together with the Lamont tritium assays.

The weighted mean T:H for the three rains is 519×10^{18}. From the New York City watershed data (see Table 2 and *Kaufman* and *Libby* [1954]), it is assumed that the normal T:H of the Hudson is 7×10^{-18}. The calculation is not very sensitive to this figure. The tritium concentration of the Hudson was raised to 28.8 by the three rains. The fraction f of the River runoff which is from those rains can be found: $7(1 - f) + 519f = 28.8$, therefore $f = 0.043$.

The total discharge of the Hudson River at Palisades (U.S.G.S. Water Resources Branch, 1954 unpublished data) in terms of the average depth over the whole drainage basin was 3.90 cm for this period. The portion of the discharge which was new water was, therefore, 0.17 cm. Since the total precipitation with increased radioactivity was 4.72 cm, 3.6 pct of the rain entered the stream directly. The remainder entered the water table or re-evaporated.

A factor which could affect this figure is the retention of some precipitation as snow in the mountain areas. Twenty out of 21 snow gage stations in the drainage basin showed no snow on the ground on March 28 [*U.S. Weather Bureau*, 1954]. Only one station (Bennetts Bridge) had snow. Since this is only one station and it recorded six inches (about one to two cm water equivalent) the effect will be neglected. Any such effect would make the 3.6 pct figure a minimum.

It is probable that a greater fraction of the rain was entering the stream during precipitation. This water would flow past Palisades within a very few days after precipitating and thus would not be recorded by the March 30 collection. This effect also makes the 3.6 pct a minimum.

Another factor which makes this figure a minimum involves runoff to lakes. To the extent that the lakes then supply the Hudson, the outflow would be diluted by the older lake water. This effect is small for the Hudson.

Tecolote tunnel—The Tecolote tunnel was built to carry water from the Santa Ynez Valley to the Pacific Coast at Goleta in Southern California. During its construction considerable water was encountered which increased rather regularly in temperature from both ends toward the center of the tunnel. Temperatures as high as 117°F were encountered.

It was decided to sample both the hot water and the cooler water for tritium. R. E. Trefzger of the U.S. Bureau of Reclamation supplied the samples and the temperature data. The object of the analyses was to determine the source of the water and to set limits on the relative amounts of meteoric and juvenile water. The tunnel was cut through moderately to steeply south-dipping Cretaceous and Tertiary siltstones, sandstones, and conglomerates. These strata are cut by several reverse faults.

It will be assumed that the mean natural tritium content of the rain in the area is 4×10^{-18} (based on the one Santa Barbara rain of von Buttlar and Libby). The Pacific Ocean rains discussed earlier [*von Buttlar* and *Libby*, 1955] average about 0.8×10^{-18}. Thus, if anything, the rain estimate is high. The two tritium concentrations are 16.5 and 75.4 respectively in these units. It is only during the spring and summer of 1954 that such values could be achieved, since the samples were collected in January 1955. Thus, it is evident that it took less than nine months for this water to reach the tunnel. It is noteworthy that the higher tritium content sample was the hot water and it was flowing faster (50 as compared to 10 gal/min).

If the mean tritium content of the rain is estimated as 200×10^{18} for the period involved, rain could account for 6 to 31 pct of the sample (depending on the sample). The presence of a pre-existing water table could dilute this rain to the observed value but be of older rain origin itself. Thus the portion of meteoric water is at least 31 pct in one case and could account for all of the water.

THE PRODUCTION RATE OF TRITIUM

Several estimates of the rate of tritium production have been made. These can be broken down into calculations based on the cosmic-ray flux data plus study of the nuclear reaction cross sections and those based on a material balance of a

TABLE 7 – *Production rate of tritium based on cosmic-ray flux and nuclear cross sections*

Reaction	Incident particle energy	Cross section	Tritium production	Investigator
	Mev	cm × 10^{27}	$H^3/cm^2/sec$	
$N^{14}(n, t)$	>4.4	11 ± 2	0.1–0.2	*Fireman* [1953]
$O^{16}(p, t)$ $N^{14}(p, t)$	>100	~ 30	≥0.1	*Fireman* and *Rowland* [1955]
			Sum 0.2–0.3	*Fireman* and *Rowland* [1955]
$O^{16}(p, t)$ $N^{14}(p, t)$	>100	~ 25	0.08	*Currie* and others [1956]
$N^{14}(n, t)$	<10	—	0.05	*Currie* and others [1956]
$O^{16}(p, t)$ $N^{14}(p, t)$	10–100	Estimated	0.01	*Currie* and others [1956]
$N^{14}(\mu, t)$ (γ, t)	— —	Estimated Estimated	$<10^{-5}$	*Currie* and others [1956]
			Sum 0.14	*Currie* and others [1956]
			Range 0.09–0.22	*Currie* and others [1956]

TABLE 8 – *Production rate of tritium, inventory method*

Method	Production rate	Investigator
	$H^3/cm^2/sec$	
Inventory on the Atlantic Ocean; data taken from Lake Mosvan, Sweden and the Mississippi River	0.12	*Kaufman* and *Libby* [1954]
Atlantic Ocean surface reservoir, two samples	0.16	*von Buttlar* and *Libby* [1955]
U. S. ground waters and rains, numerous samples	2	*Begemann* and *Libby* [1957]
Same data as Begemann and Libby	1.2	*Craig* [1957]
Atlantic Ocean surface water and land runoff	.75 ± .4	This paper

TABLE 9 – *Summary of data used in calculation of tritium production rate from North Atlantic budget*[a]

Source	Rate
	atoms/year
Land runoff to North Atlantic	0.1 × 10^{25} H^3
Influx to North Atlantic from South Atlantic	0.8 × 10^{25} H^3
Influx to North Atlantic from precipitation and exchange	1.2 × 10^{25} H^3
Loss from North Atlantic surface by sinking	1.3 × 10^{25} H^3
Loss from North Atlantic surface by decay	0.75 × 10^{25} H^3

Summary

Area of North Atlantic, 41 × 10^6 km^2.

Fraction of natural tritium produced below tropopause, 0.4.

Half-time of transfer from stratosphere to troposphere, 6 years.

Tritium influx from rain to North Atlantic, 0.6 ± 0.3 H^3 atoms/cm^2 sec.

Total natural tritium production rate, 0.75 ± 0.4 H^3 atoms/cm^2 sec.

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[a] Details of calculation in *Giletti* [1957].

portion of the Earth's surface. Tables 7 and 8 summarize these estimates. It is evident that the predicted rates of production from cosmic-ray calculations are lower than the rates calculated from the budget data by as much as a factor of ten. The rate calculated in this paper was arrived at in the following manner.

The budget in the North Atlantic Ocean was calculated for the North Atlantic Surface Water (the pertinent data are in Table 9). Mixing of this water was shown to be rapid down to the seasonal thermocline which will be taken as 50 m. The loss of tritium from this 50 m thick layer of water occurs via sinking, radioactive decay, and evaporation. The sinking and decay terms are readily computed (see Table 9). The evaporation term is combined with the precipitation and exchange terms below.

Influx of tritium to the North Atlantic occurs from streams, the South Atlantic, and precipitation and exchange. The amount of tritium from land runoff is small. It was calculated from data of *Kaufman* and *Libby* [1954] and *von Buttlar* and *Libby* [1955] on Mississippi River and European stream concentrations.

It is assumed that equal amounts of tritium are added to the North Atlantic and to the South Atlantic via precipitation and exchange. If the mean residence time of a water molecule in each of the two surface layers (north and south) is taken as ten years, it is possible to derive the tritium concentration of the South Atlantic surface. This calculation yields a natural T:H = 0.6×10^{-18}. This value is used as the tritium concentration of the 6×10^6 m^3/sec of water [*Sverdrup* and others, 1942] entering the North Atlantic from the south.

It was assumed that about 50 pct of the tritium which fell on North America re-evaporated and entered the ocean by precipitation or exchange. This means that only two-thirds of the new tritium entering the North Atlantic was produced over the North Atlantic. Part came from the continent. Thus, while 1.2×10^{25} H^3 atoms enter the North Atlantic annually, only 0.8×10^{25} are produced over the North Atlantic. This yields a net flux of 0.6 ± 0.3 H^3/cm^2/sec.

The actual production rate is larger than this value because about 60 per cent of the production occurs above the tropopause. The half-time of transfer downward across the tropopause is taken as six years [*Stewart* and others, 1955; *Libby*, 1956]. This delay means that some tritium decays in the stratosphere (about 20 pct of the total produced). The net tritium production becomes 0.75 H^3 atoms/cm^2/sec. A detailed calculation is given in *Giletti* [1957].

This critical assumptions in this calculation are that the North Atlantic is large enough to be representative of the Earth and that the 1953 data represent a water system uncontaminated by man-made tritium. These are currently being studied further. It is noteworthy that *Craig's* [1957] calculation based on a continental budget gives 1.2 H^3 atoms/cm^2/sec. A recent calculation by *Begemann* and *Libby* [1957] using a continental balance yields a rate of 2 H^3 atoms/cm^2/sec.

It is possible that a new source of tritium may have to be sought if the budget calculations are right. The error in the present budget computation almost overlaps the theoretical values, but the other authors' values are somewhat too large for this.

The total tritium inventory was calculated based on the following data. A tritium concentration of 1.0×10^{-18} was assumed for the upper 50m in the oceans. Another layer of T:H = 0.2×10^{-18} was assumed from 50m to 200m depth. The resulting weight of tritium for 3.6×10^8 km^2 is 9.6 kg. Allowing for ground-water storage and the small atmospheric tritium reservoir, the total tritium inventory was probably about 12 kg. Since the surface ocean T:H doubled in 1954, the inventory has also doubled.

SUMMARY AND CONCLUSIONS

The initial objective of this study was the establishment of rates of circulation of ocean water masses. It soon became apparent that a more extensive survey was required; one which encompassed the lands and the atmosphere. As a result of the study the following conclusions are drawn:

(1) A steady-state analysis of tritium in natural waters is no longer possible. The total amount of natural tritium on the planet before 1954 was about 12 kg. This inventory has at least doubled since 1954 as a result of thermonuclear tests by the United States and other governments.

(2) Precipitation showed the greatest effects of thermonuclear activity, with the Lamont T:H values changing from a mean of 8×10^{-18} in normal times to 1240×10^{-18} at the peak time in the test series. Following the tests, the maximum half-time of washout from the troposphere was found to be 35 days. The new base level was about 19×10^{-18} and this increase over the previous value of 8 may be due to slow downward exchange of extra tritium from the stratosphere.

(3) The pre-thermonuclear-age tritium concentration of surface ocean waters has been shown by this study to be 1.0×10^{-18}. This value is important to all subsequent work in tritium concentrations since it represents the natural level.

(4) The ocean surface in 1954 had a T:H = 1.9×10^{-18} and probably reached 2.0 after all the debris had come out of the troposphere. Thus the value for the surface ocean doubled.

(5) The surface ocean water mixes down to the seasonal thermocline in one year, but the distribution is patchy and several years are probably required to smooth this out.

(6) The North Atlantic Central Water appears to be 25 years old off the coast of Portugal and in the southwestern North Atlantic. This is based on a mass flow principle with the convergence at about 40° N in the western Atlantic. If lateral mixing is the dominant effect, then the upper portion of this water has a mean age of 25 years and an equivalent of $<2 \times 10^6$ m^3/sec is transmitted downward at the convergence.

(7) Three samples collected at the bottom in the North Atlantic showed measurable tritium. It is possible that some surface water sinks at high

latitudes and flows rapidly along the bottom without mixing completely.

(8) The tritium contents of European rains and streams in August 1954 are of the same order of magnitude as in the United States for comparable latitude.

(9) The rather hot waters in the Tecolote Tunnel were observed to be less than nine months old, showing that the steeply dipping strata plus the various faults permit rapid flow once drainage is started.

(10) Lakes and streams in the United States and Europe were quick to reflect the increased tritium content of rains in 1954. Marked increases were observed within two weeks after the first 'hot' rains. However, the surface runoff still accounted for the major portion of the contamination carried by the streams. The capacity of the reservoir of surface water determined the extent of the contamination. Small reservoirs reacted with much higher T:H values.

(11) The direct runoff of precipitation from the ground surfact to streams was $\geq$ 3 pct for the Hudson River basin in 1954.

(12) A calculation of the cosmic-ray production of tritium was made using the Atlantic Ocean as the reservoir on which the material balance was made. The production is assumed to occur both above and below the tropopause with 40 pct occurring below. A half-time of removal from the stratosphere of six years is chosen. The production is calculated as 0.75 ± 0.4 T atoms/sec cm^2 of Earth's surface. The influx to the sea is 0.6 T atoms/sec cm^2 and the remainder is accounted for by decay in the stratosphere. This is somewhat higher than previous estimates based on known cosmic-ray reactions.

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Distortion in Continental Triangulation

CHARLES A. WHITTEN

Abstract—**The present network of triangulation in the United States is the result of adding individual surveys season by season to the existing framework. The last major readjustment of the national net was in 1927. The skeleton framework of that date is now covered by crisscrossing arcs and area nets of first- and modified second-order triangulation. When each survey is mathematically adjusted to be consistent with the previously adjusted surveys, small twists and strains are introduced. These tend to accumulate through successive adjustments to a point where observations are distorted far beyond normal expected errors. Efforts are made to keep this distortion to a minimum by increasing standards of accuracy for the basic framework and by planning surveys to give strength to the net as well as furnishing desired information for engineering and scientific projects. Methods of computation which will give complete information on internal accuracy and checks must be used. Also, through the application of modern electronic computing equipment, it is possible to adjust the maximum size net, thereby reducing probability of extreme distortion.**

A basic requirement for the construction of most large-scale engineering projects is a complete set of plans or master drawings on which all details of every phase of the project have been illustrated. These are needed before any construction can be undertaken. If the engineering project also has a scientific use, volumes of additional specifications and descriptive material will be provided in advance. This is just normal procedure.

Now, let us consider briefly the development of an engineering structure for which there have been no detailed preliminary plans for the entire project. The building-up of a continental network of triangulation is analogous to this. In such a network individual surveys are connected to each other in a manner to permit continuous computation. Rigid specifications must be followed in the execution of each survey. This is similar to a requirement that the material used in a structure must meet certain standards. However, when the urgency of related engineering activities hastens the mathematical adjustment of these individual surveys, the result is a network that is of piecemeal construction rather than one that is completely homogeneous.

Since we have compared a network of triangulation to an engineering structure we must also use an engineering approach insofar as possible, in the development of it. The progress that has been made in the last hundred years is remarkable. Our predecessors were very practical in their treatment of the accumulated survey data, and the history of the horizontal-control datums in North America is well known. However, in the past each generation seemed to be faced with a fundamental problem of fitting new surveys to the then existing net. This same problem faces us today. It is the normal consequence of attempting to make a large structure rigid by adding one member at a time to it.

The early surveys in this country consisted of arcs of triangulation crisscrossing each other to form loops 50 to 60 mi on a side. These loops are now being filled with networks of single triangles covering the area. The area networks are very strong in a mathematical sense and frequently when they are adjusted into the previously adjusted loops, excessive corrections are placed on the original observations for the mere requirement of computational consistency throughout the net. This distortion is caused by systematic weaknesses in the control framework. The magnitude of the distortion in the area net depends upon the distortion that exists in the framework. Let us compare the situation to a watch crystal. If the frame has been damaged or squeezed out of shape by even an infinitesimal amount, there is no way to fit the crystal, and any attempt to do so will surely fracture it. The solution is to repair the frame.

That, very simply, is our problem today. The fundamental framework in sections of the country has become slightly deformed through this process of adding survey to survey. The error in geographic position is not significant and cannot be detected on any map. However, the errors in azimuth or length of individual lines are large enough to be detected and even be disturbing to the users of control data.

This problem must be resolved. One solution would be a total and simultaneous readjustment of all surveys. Personally, I would not recommend such a project until the network has been fully completed. Our present approach for a workable solution to the problem is based on three major guide lines.

First, the fundamental framework must be able to meet all standards of accuracy. Experience has shown us that if any portion of a first-order arc has scale errors approaching 1 part in 25,000, the adjustment of adjacent networks will be totally unsatisfactory [*Whitten*, 1957]. Therefore, the minimum standard of accuracy for first-order triangulation was recently raised to 1 part in 50,000. Most of our continental framework meets this higher standard, and when it is known that a portion of it falls below the minimum requirement, the original survey is strengthened.

This strengthening operation brings us to our second guide line. The development of instruments for measuring base lines electronically with either light or radio waves has provided us with a means of correcting these errors of scale. Base lines may be easily inserted into the older surveys and, through recomputation, the lengths of lines in the original survey will have the required accuracy.

The problem is more involved than that. Merely adding a base line and correcting one line in an arc of triangulation may produce further distortion. An arc is fixed in over-all length by the latitudes and longitudes of the end points. This then fixes the over-all scale. If we correct some of the lengths in an arc by a positive amount, other lengths in the same arc must be shortened in order to maintain the fixed over-all length. Generally, it is necessary to 'relax' these fixed end points and readjust a fairly large system of crisscrossing arcs so that the distribution of the changes in scale will not create any further abnormal distortion.

The methods to be used in these major readjustments also require guides. Here again, we can use electronic tools. Modern high-speed computers can be used to test the adequacy of a proposed readjustment. Internal checks built into a computer program provide the means of determining the accuracy of the adjusted values. Closures of azimuth, length, latitude, and longitude may be obtained directly from the solution of a set of normal equations which have been formed from a series of observation equations, using the classical method of adjusting by the variation of coordinates, and to which have been added the proper condition equations containing the true closures of these external controls. This special technique of combining the two types of equations was first described by Helmert and, in more recent times, by *Stearn and Braaten* [1948]. The use of this technique, with the further adoption of the Cholesky method for solving normal equations, presented the programmers of the high-speed computer with a special problem of handling complex numbers. This was only one of many tricky processes for which machine codes and instructions were needed. The application of electronic computers to geodetic problems has broadened the mathematical experience and knowledge needed for the development of our basic network.

In conclusion I wish to state again that it has been the urgent need for adjusted results of individual surveys that has been responsible for the lack of homogeneity in the continental network. Through our efforts to be practical in furnishing data as soon as possible we have lost some of the over-all strength that might have been obtained if this urgency had not existed. In the years immediately ahead of us we will find it necessary to revise portions of the federal net for these reasons that I have described. Naturally, there will be considerable inconvenience to engineers who have used control data with the confident belief that the coordinates would not be changed. I hope that they will overlook this inconvenience and recognize that they will be using values which are more accurate and also rigorously connected to a stronger continental network.

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Geodetic Control in Jungle Areas

CARL I. ASLAKSON

Abstract—Oil companies are frequently faced with the problem of delineating oil concession boundaries in unmapped areas. Such boundaries are often defined by latitude and longitude lines drawn on outline maps. Usually, time limits are set for defining the concession boundaries which preclude the use of conventional surveying techniques. This paper describes the manner in which Aero Service Corporation employed shoran trilateration and shoran controlled photography for geodetic control in the Peten area of northern Guatemala. This method is commonly known as the SCP or secondary control point method.

One of the difficult problems facing oil companies is the physical demarcation of concession areas. Frequently, many companies are granted concessions in unsurveyed countries. Often, such concessions are defined by lines drawn on maps which are little better than outline maps. This was the problem which 15 oil companies faced in Guatemala in 1956. Figure 1 shows the Peten region in northern Guatemala. No geodetic control existed in the entire region, the greater part of which was almost impenetrable jungle. The concession agreements specified detailed boundary surveys and the time allotted for the survey was brief. Hence, the problem consisted of: (1) providing the necessary geodetic control to serve as initial survey points; (2) meeting time limits specified in the concession agreements; (3) satisfying the Guatemalan government and the concessionaires as to the accuracy of the resulting control.

In addition to the above requirements an airborne magnetometer survey was to be made over the entire Peten area. The Peten region had previously been photographed. However, because of the lack of control, no mosaic could be compiled. Owing to time limitations, no consideration could be given to conventional control methods. The possible existence of deflections of considerable magnitude precluded the use of astronomic positioning. Hence, it became necessary to employ shoran trilateration combined with shoran secondary control points, commonly referred to as SCP's. This was the project undertaken by Aero Service Corporation. The aircraft used was a DC-3 flown to Guatemala after the instrumentation had been installed in the United States. H. Meier was the geodetic engineer in charge of the technical direction.

SCP's or shoran secondary control points in the Bahama Islands—The writer first began development of the technique of establishing ground geodetic control by means of shoran controlled photography at Denver, Colorado in 1946. This technique was first used extensively in 1949 to 1951 in the Bahama Islands during the Air Force Missile Test Center Hiran Survey. Figure 2 indicates numerous islands which were positioned by this method. Obviously, it would have been uneconomical to establish main scheme Hiran stations on all the islands shown.

The SCP method—Briefly, the SCP method consists of selecting the point to be positioned, flying across the point in four directions with the cameras operating at minimum exposure interval with shoran operating during these flights, the shoran recorder being synchronized with the photogrammetric camera. A plot of typical SCP flights is shown in Figure 3. The coordinates are the computed plane coordinates of the principal points of each photograph. These relative positions are computed from the shoran data. Figure 4 shows a typical SCP photograph. Note that the point circled is a small clearing in the jungle, within which a point is marked with a white cross made with lime. Figure 5 is one of these photographs with the clearing area enlarged to show the cross. It should be noted that the SCP flights are made with flight headings in four directions, thus increasing the probability that tip and tilt errors are minimized in the final position.

Computing the SCP—The steps in obtaining the SCP position are: (1) Prepare a graphical plane coordinate plot of the computed positions at the mean scale of the photographs (Fig. 3). (2) Mark the selected SCP point and principal point on each photograph. (3) Scale the distances from the principal points to the SCP. (4) Plot an approximate position of the SCP on the plane coordinate plot. (5) Make a simple least-square adjustment to cause all scaled distances to converge at the same point. The constant term in each observation equation is the difference between the computed lengths to the

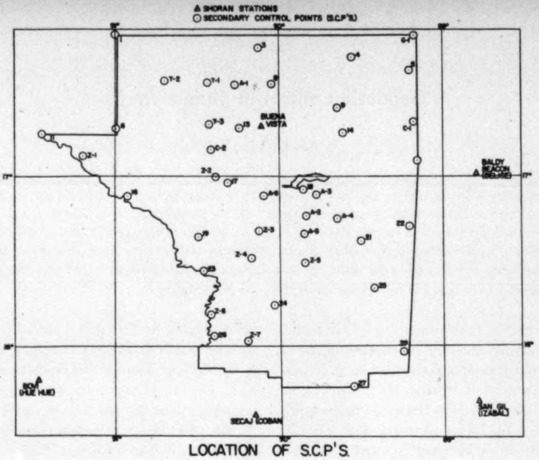
SHORAN STATIONS
SECONDARY CONTROL POINTS (S.C.P'S)
BUENA VISTA
BALDY BEACON (BELIZE)
(HUE HUE)
SECAJ (COBAN)
SAN GIL (IZABAL)
17°
16°
90°
LOCATION OF S.C.P'S.

FIG. 1 – Location of secondary control points and shoran stations determined during Guatemalan air survey

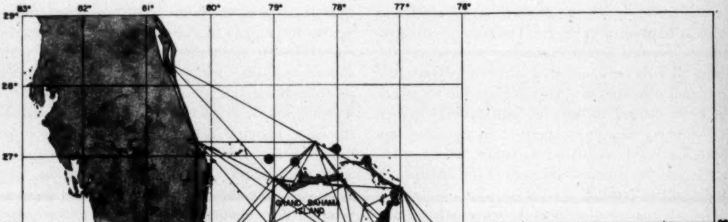
83°
82°
81°
80°
79°
78°
77°
76°
75°
74°
73°
72°
29°
28°
27°
26°
25°
24°
23°
22°
21°
20°
GRAND BAHAMA ISLAND
ANDROS ISLAND
CAT ISLAND

FIG. 2 – Trilateration lines and secondary control points established during 1949–51 Bahama Island survey

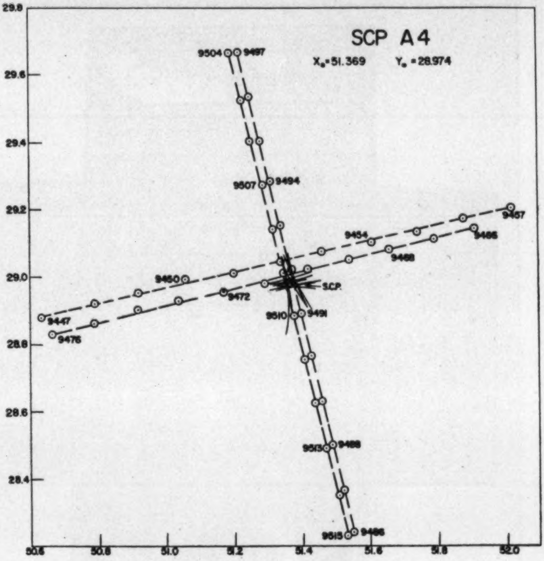

FIG. 3 – Typical secondary control point flight pattern followed by Aero Service

assumed position and the lengths as scaled on the photographs. (6) Convert the adjusted plane coordinate position to geodetic coordinates. Note that the final SCP position is dependent on the use of shoran coordinates measured with respect to one pair of control stations.

Control stations for Peten SCP's—Figure 6 shows the control stations from which all the Peten SCP's were located. Stations Huehue, Coban, and Izabal were first-order triangulation stations on the same arc. Belice was a British Honduras station on a separate datum for which an approximate datum tie had been made. It was necessary to verify this datum tie and also to establish a fifth control station, Buena Vista. Hence, all distances shown in Figure 6 were measured by the shoran line-crossing technique and the trilateration net was computed. The longest line was from Huehue to Belice and was over 196 mi. in length. The uncertainty of the datum tie at Belice had been given as ±20 ft. Inasmuch as the shoran trilateration position of this point agreed with the approximate position by 18 ft., the position as given in the approximate datum tie was held in the adjustment. The six known distances thus afforded an excellent means of obtaining an absolute calibration of the shoran distances. This calibration was applied to all SCP measurements. It showed the characteristic change with distance attributable to normal signal strength attenuation. The final distribution of the SCP's is shown in Figure 1.

Altitude control—Absolute altitudes as well as differential heights are required for SCP and shoran reductions. Calibrated pressure altimeters, radio altimeters, and airborne psychrometric measurements were used in obtaining accurate altitudes. The radio altimeter was calibrated at San José Airport against photogrammetric heights. The corrections were found to be a function of height above terrain and were of considerable magnitude. This effect was predicted inasmuch as the correction is a function of signal strength. By a number of flights between sea level and check surfaces in the heart of the Peten area, the altitude of the check surfaces was well established. These check surface flights were made by flying at a constant pressure

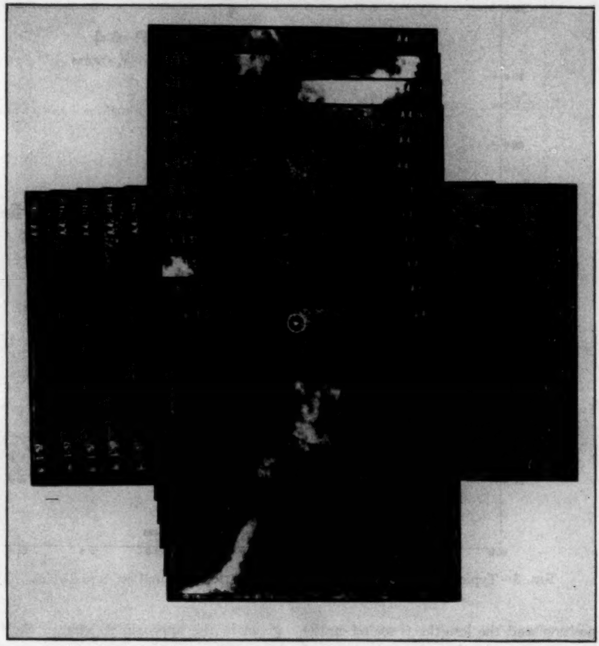

FIG. 4 – One series of overlapping photos made during secondary control point flight in El Peten area; two such series are required per flight to minimize aircraft tip and tilt errors; circled point shows jungle clearing and SCP cross

level, obtaining psychrometric data on the flight, computing the slope of the isobaric surface and applying this correction as well as the radio altimeter height differences. After the check surfaces were established, they, in turn, served in a similar manner for determining absolute altitudes of the SCP and trilateration flying heights.

Time required for project—Although the entire project required slightly less than four months, the geodetic control phase required only 38 days, the remainder of the time being devoted to magnetometer surveys. Thus, the establishing of basic control for an area of about 12,000 sq. mi. was slightly more than one month.

Accuracy of SCP's—A complete evaluation of SCP position accuracy has never been made. The internal consistency as revealed from computations is very high, seldom exceeding ±10 ft for the probable position error. This is with respect to the two control stations used and, of course, is not a realistic measure of error. On two occasions, SCP positions have later been verified by triangulation. In one case, the resultant position error was 40 ft and in the second case, it was 100 ft. The accuracy is such that SCP's serve as excellent control for 1:50,000 mosaics using radial plotting methods. This accuracy could be improved by flying the same SCP from a second pair of stations and adjusting the position from all four stations.

Conclusions—Shoran SCP's provide a valuable means of rapidly extending lower-order control over areas difficult of access such as jungle areas.

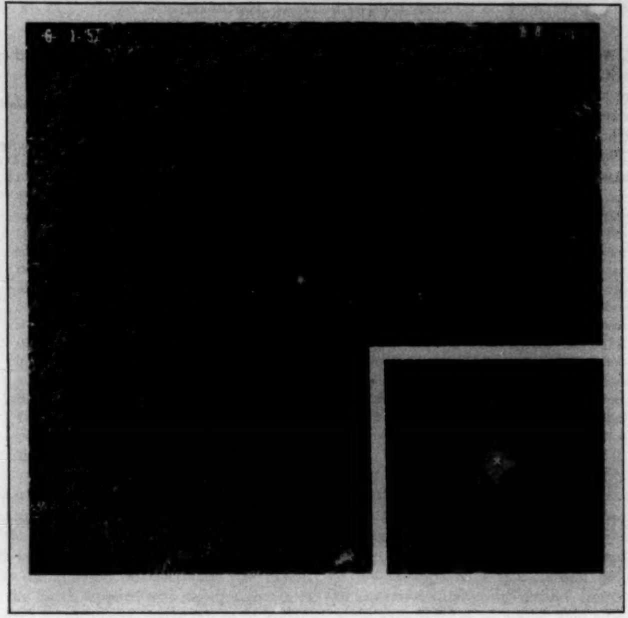

Fig. 5 – Single photo and its enlarged section show jungle clearing and secondary control point marker

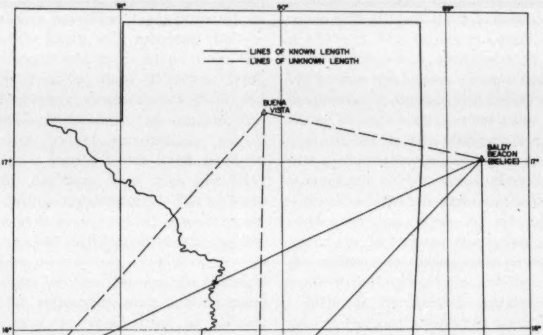
91°
90°
89°
LINES OF KNOWN LENGTH
LINES OF UNKNOWN LENGTH
BUENA VISTA
BALDY BEACON (BELICE)
17°
16°
BOVI (HUE HUE)
SECAJ (COBAN)
SAN GIL (IZABAL)
SHORAN TRILATERATION NET

Fig. 6 – Shoran station locations and trilateration net employed for determination of secondary control points during Guatemalan survey

Recently, Aero Service Corporation completed an extensive SCP project in the Arabian desert. Whenever large areas have been photographed but no control is available, shoran SCP's provide the most rapid method presently known for obtaining the control. This technique is of great value to oil companies who are granted foreign concessions, the physical boundaries of which are defined on inadequate maps.

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Airborne Measurements of Atmospheric Electricity

J. H. KRAAKEVIK AND JOHN F. CLARK

Abstract—An experimental investigation of the variations of atmospheric electric quantities in space and time was conducted. A review of past measurements reveals several inaccuracies and inconsistencies which stimulated the investigation. The simultaneous measurement of both polar conductivities, of potential gradient, and of several meteorological quantities from a multi-engine airplane, and the derivation of other atmospheric electric variables, are described. Altitude 'profiles' of conductivity and potential gradient up to 6 km obtained on a representative sounding over the Chesapeake Bay show a secondary exchange layer above the more common surface exchange layer. The space-charge density profile exhibits positive charge concentrations at the tops of these layers, near the bases of the associated temperature inversions. Upward convection of positive space charge causes the computed conduction-current density within the exchange layers to be some 40 pct higher than its relatively constant value above the layers. The product of columnar resistance and current density, employed by previous workers to obtain atmospheric potential, provides erroneous values whether the conduction current near the Earth's surface or the average value over the entire altitude range is used. On the basis of a 6-km atmospheric potential of 327 kv obtained from the integrated potential gradient, the true extrapolated total potential of the high atmosphere is 341 kv at a time near the diurnal maximum.

Introduction—After it was discovered in the 18th century that the Earth possesses a negative charge during fair weather, and that the atmosphere is an imperfect insulator, one of the basic questions of atmospheric electricity was raised: How is the Earth supplied with negative charge to compensate for the loss of charge caused by atmospheric conduction? During the past fifty years, measurements of potential gradient and atmospheric conductivity have been made primarily on land surfaces of the Earth, with occasional observations over the oceans and in the Arctic. From this vast body of statistical data [*Whipple*, 1929], together with aircraft measurements [*Gish* and *Wait*, 1950], the basic problem of atmospheric electricity has been rather convincingly solved: Negative charge is carried to the Earth by lightning and point discharge from trees and other high objects during thunderstorms. The airborne measurements have also provided some information on the vertical distribution of atmospheric electric variables.

Accepted views of the fair-weather electrical properties of the atmosphere prior to the present investigation may be summarized as follows: The negative Earth and positive high atmosphere may be regarded as a spherical condenser, according to *Gish* [1951], with the atmosphere a leaky dielectric of some 200 ohms resistance. This atmospheric condenser is kept charged to a potential of approximately 360 kv by world-wide thunderstorm activity, which supplies the condenser with some 1800 amp continuously to maintain equilibrium. The stability of the potential is uncertain, although on the average it varies diurnally by nearly 20 pct about the mean. The conductivity of the atmosphere is not uniform but increases almost exponentially with altitude from its average ocean surface value of 2.5×10^{-14} mho/m [*Chalmers*, 1949; *Gish*, 1944]. Consequently the potential gradient exhibits an almost corresponding decrease with altitude from its average surface value of 130 v/m. This results in a positive atmospheric space charge which decreases with altitude [*Gish*, 1949]. The conduction current density, which is the product of conductivity and potential gradient, has an average ocean surface value of 3.2×10^{-12} amp/m², but shows a tendency to decrease slightly with altitude [*Everling* and *Wigand*, 1921]. Surface atmospheric electric measurements, usually made within the turbulent and frequently contaminated surface exchange layer, are subject to local variations due to weather and pollution, which mask the variation in atmospheric potential caused by world-wide thunderstorm activity.

Although the general features of the atmosphere's electrical properties are understood, there remain a number of detailed discrepancies. For example, altitude distributions of potential gradient have been obtained from balloons but these are inaccurate, according to *Schonland* [1953], owing to "the distortion of the field by free and induced charges on the balloon." From these inaccurate balloon measurements estimates of the total atmospheric potential have been made by integrating the potential-gradient distributions.

A second method which has been used for estimating the total potential is to measure the conductivity distribution with altitude and from it obtain the total columnar resistance (resistance of a column of air 1 m^2 in cross section extending from the Earth to the high atmosphere). During the time conductivity is measured at altitude, the current density is measured at the Earth's surface. If the current density is assumed to be the same at all higher altitudes, the total potential is equal to the product of the columnar resistance and average current density. These estimates of total potential vary from 200 to 400 kv, according to *Gish* [1949].

As a second related example, the condition of quasistatic equilibrium in the atmosphere requires the vertical current density to be constant with altitude in fair weather. However, the only simultaneous airborne measurements of conductivity and potential gradient [*Everling* and *Wigand*, 1921] provide a current density which decreases with altitude.

Most past measurements of atmospheric electric variables have been made from the Earth's surface, where statistical analysis of large amounts of data is required to extract the descriptive features of atmospheric electricity. It is the purpose of this paper to show how the conductivity and potential gradient are obtained directly by means of an airplane, and used to derive the columnar resistance, current density, atmospheric potential, and space charge density, up to altitudes well above the surface exchange layer; and to present experimental altitude distributions of these quantities representative of the atmosphere over the Eastern United States.

Measurement techniques—Although its altitude capability is much less than that of balloons and rockets, the airplane was chosen as the research vehicle for a number of compensating reasons. First, according to *Gish* [1949], more than 80 pct of the total atmospheric potential lies below the ceiling of the aircraft (6 km), and that portion inaccessible to measurement is fairly predictable because the conductivity of clear air does not vary appreciably with time at high altitudes. The airplane is more accurate than the balloon in the measurement of ambient potential gradient, because its conducting skin and geometrically-invariant configuration can be permanently calibrated for electric field distortion. It provides the most precise control of position and altitude, the best chance of using the same instruments for repeated measurements, and the best facilities for an observer to accompany his instruments. Furthermore it has a relatively large space and weight capacity, and can be used both for transportation and as a research vehicle at almost any point on the Earth.

In this study each vertical 'sounding' of the atmospheric electric variables is made over a fixed geographic locality. Data are taken in steps during descent from the airplane's ceiling (6 km), with the aircraft maintaining constant heading and speed for several minutes at each altitude. An entire sounding requires approximately 70 min. Each sounding is taken in fair weather, in which the maximum cloud cover at any altitude is 10 pct, and there is no precipitation within 50 km.

A P4Y airplane was instrumented as a mobile laboratory (see Fig. 1) to measure and record continuously both polar conductivities, potential gradient, aircraft charge, and atmospheric temperature, pressure and relative humidity. Three visual recorders provide up to twelve synchronized channels of data. Time checks, geographic locations, weather summaries, and all adjustments of either the research instrumentation or the aircraft operating conditions are reproduced by means of an aural recorder.

The atmospheric polar conductivities are measured simultaneously by means of two Gerdien-type cylindrical condensers, through which air flows continuously. The accelerating voltage is applied to the outer cylinder of each condenser while the ion current to the central electrode is measured with a vibrating-reed electrometer. Calculations and airborne measurements both demonstrate that the conductivity meters are always operated on the linear portion of their current-voltage characteristics. Each polar conductivity is obtained from the difference in measured current for two separate accelerating voltages. It was also verified experimentally that the measurement of conductivity, which is accurate to within 5 pct, is not influenced by the charge normally residing on the airplane during fair weather [*Kraakevik*, 1958]. The total conductivity λ is the sum of the positive and negative conductivities.

In fair weather the positive atmospheric potential gradient $\partial V/\partial Z$ is vertical and is numerically equal to the negative electric field E. These quantities are measured with three grounded-rotor induction-type electric field meters located at the

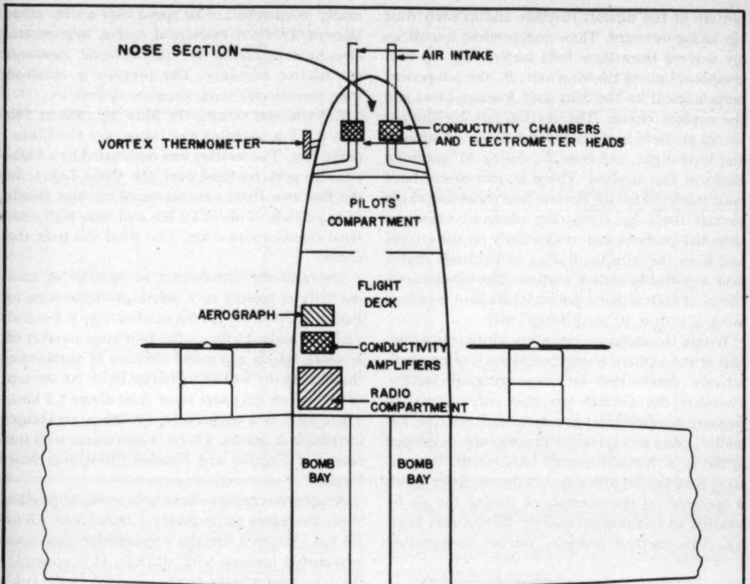
NOSE SECTION
AIR INTAKE
CONDUCTIVITY CHAMBERS
AND ELECTROMETER HEADS
VORTEX THERMOMETER
PILOTS' COMPARTMENT
FLIGHT DECK
AEROGRAPH
CONDUCTIVITY AMPLIFIERS
RADIO COMPARTMENT
BOMB BAY
BOMB BAY
BOTTOM EFM
POWER REGULATION AND DISTRIBUTION
NAVIGATIONAL INSTRUMENTS
CONDUCTIVITY METER CONTROL PANEL
AURAL RECORDER
VISUAL RECORDERS
AFTER SECTION
EFM AMPLIFIERS
60 CPS INVERTERS

FIG. 1 – Sectional view of airplane instrumentation

bottom of the aircraft fuselage and at each wing tip facing outward. Three independent quantities are derived from these field meters: E_y, the field component along the wing axis; E_z, the component perpendicular to the wing and fuselage axes; and the airplane charge. The vertical fair-weather potential gradient is obtained from E_z during straight and level flight, and from E_y during 30° precision banks of the airplane. These measurements have been corrected for the electric field distortion of the aircraft itself by comparing observed values of potential gradient and conductivity on the ground and from the airplane during low-altitude flights over a portable surface station. The absolute accuracy of each airborne potential gradient measurement is within 10 pct [*Clark*, 1957].

Within the exchange layer, the altitude distribution of atmospheric electric variables is often qualitatively determined by meteorological factors. Therefore the aircraft was also instrumented to measure temperature, pressure, and relative humidity, using an experimental aerograph developed at the U. S. Naval Research Laboratory. Temperature is measured with a vortex thermometer which is operated on the principle of cooling the air by rotation to compensate exactly for the ram heating. This method provides free-air temperature nearly independent of air speed over a wide range [*Ruskin*, 1954]. A cylindrical carbon hygrometric element surrounding the thermometer measures the relative humidity. The pressure is obtained from the aircraft static pressure system.

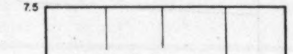

Fig. 2 – Altitude distribution of conductivity

Experimental results—On May 24, 1956 at 18h 00m GMT a sounding was taken over the Chesapeake Bay. The weather was dominated by a high-pressure area centered over the Great Lakes. In the Bay area there were scattered cumulus clouds at an altitude of about 1.2 km and some high scattered clouds above 6 km. The wind was from the north.

The altitude distribution or 'profile' of conductivity is plotted on a semilogarithmic scale in Figure 2. Up to 1.2 km the conductivity is low and variable, undoubtedly owing to a large number of aerosols, which are mixed because of turbulence throughout the surface exchange layer. At the top of the surface exchange layer (just above 1.2 km), where there is a temperature inversion, an abrupt increase in λ occurs. This is in agreement with the results of *Sagalyn* and *Faucher* [1954] over New England.

A rather uncommon feature of overland profiles is the secondary exchange layer from about 1.3 to 2.3 km. Above 3 km the conductivity shows an exponential increase with altitude. It is apparent that the conductivity profile obtained in the contaminated air above the Chesapeake Bay departs considerably from the simple exponential distribution obtained in the relatively clean air above Greenland [*Kraakevik*, 1958]. The ratio of negative to positive conductivity above the two exchange layers is 1.1, in agreement with that obtained in Greenland.

The corresponding potential-gradient profile is shown in Figure 3. This curve is almost a reflection of the conductivity distribution, with abrupt decreases in potential gradient just above 1.2 and 2.1 km corresponding to increases in conductivity at the same altitudes. However, in contrast to the variable conductivity, there is a smooth decrease in potential gradient with altitude in the surface exchange layer, necessarily due to the presence of a positive space charge. Above 3 km the measured values of potential gradient depart from the smooth exponential curve by less than 10 pct.

Other atmospheric electric variables may be derived from the measured values of conductivity and potential gradient. The conduction current density j is obtained from

$$j = \lambda E \qquad (1)$$

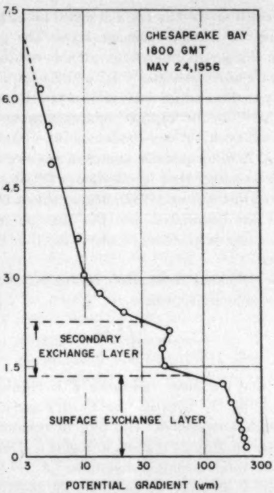

FIG. 3 – Altitude distribution of potential gradient

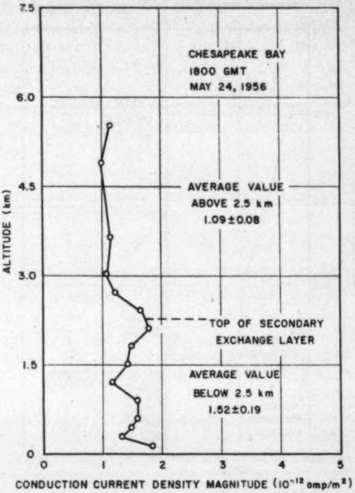

FIG. 4 – Conduction-current density profile

and consequently is negative in fair weather. A plot of conduction current density against altitude is given in Figure 4. Above 2.5 km j is almost constant with altitude, having an average value of -1.09×10^{-12} amp/m², with a standard deviation of only 7 pct. This is in agreement with the classical view [*Chalmers*, 1949], in which the conduction current density is assumed constant with altitude.

Figure 4 shows that within the exchange layers j is higher on the average and more variable than above the layers. This can be explained by the presence of a convection current density j_c, where

$$j_t = j + j_c \tag{2}$$

and j_t is the total current density. The mechanical upward transport of positive space charge results in a convection current of opposite polarity from the conduction current. Thus in order to maintain the total current sensibly constant, j becomes more negative, having an average value of -1.52×10^{-12} amp/m² ± 13 pct within the exchange layers. If it is assumed that j_t is constant with height over the entire altitude range, and equal to the average value of j above 2.5 km, then an average convection current density of $+0.43 \times 10^{-12}$ amp/m² below 2.5 km is obtained. It is evident that within the exchange layers the convection current can at times be an appreciable fraction (for example, 40 pct) of the total current.

Space-charge density is obtained from the altitude variation in potential gradient. Since the fair-weather potential gradient is vertical, the space-charge density ρ is derived from Poisson's equation, and in mks units is

$$\rho = -\epsilon \frac{\partial^2 V}{\partial Z^2} \tag{3}$$

where ϵ is the atmospheric dielectric constant. This reduces to

$$\rho = -55.2 \frac{\partial^2 V}{\partial Z^2} \tag{4}$$

where ρ is in elementary charges per cm³, and $\partial^2 V/\partial Z^2$ is the rate of change of potential gradient with altitude in v/m², obtained from $\partial V/\partial Z$ by numerical differentiation between experimental points.

Space-charge density and temperature profiles for May 24 are given in Figure 5. The histogram presentation of ρ is used because of the inaccuracies in taking the derivatives of experimental data. The largest positive values of space charge occur at and just below altitudes where there are temperature inversions, which correspond to the tops of the exchange layers. A comparison with

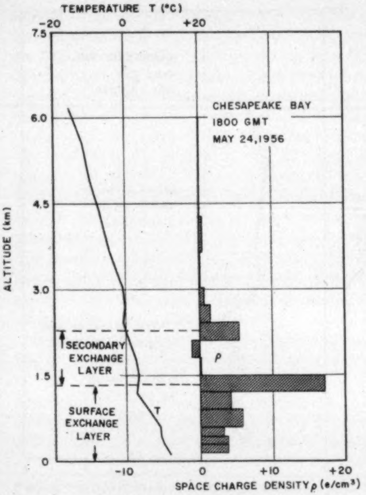

FIG. 5 – Space-charge density and temperature profiles

Figures 2 and 3 shows that changes in conductivity and potential gradient are much more sensitive indicators of tops of exchange layers than changes in temperature gradient.

The classical profile of space charge is one in which ρ decreases monotonically with altitude because of a constant conduction current flowing through a medium of increasing conductivity with height [*Chalmers*, 1949]. Since on May 24 the conductivity does not increase smoothly with altitude within the surface exchange layer (Fig. 2), if charge transport were by conduction alone the equilibrium space-charge density should vary with altitude, having both positive and negative values. However it may be seen in Figure 5 that below 1.2 km ρ is always positive and approximately constant. Thus, mechanical transport of space charge, or convection current, is required to maintain ρ relatively constant with altitude, in agreement with the current density results.

One possible explanation is that a large positive space-charge density exists below the lowest altitude at which measurements were made (150 m). The depletion of negative ions near the Earth's surface and the resulting positive space charge are normal consequences of the 'electrode effect' [*Gish*, 1951]. The positive space charge is then convected upward and is well mixed by turbulence within the surface exchange layer. The positive space-charge accumulations at the conductivity discontinuities just above 1.2 and 2.1 km are due partly to this upward convection of positive charges and partly to the 'capture' by condensation nuclei of small positive ions conducted downward from above. Another possible source of positive charge is the one suggested by ***Mühleisen*** [1956] and reiterated by ***Chalmers*** [1957], that positively charged nuclei are introduced into the atmosphere from combustion and other sources on the Earth's surface.

The columnar resistance r is obtained from the total conductivity, where

$$r = \int_0^Z \frac{dZ}{\lambda} \tag{5}$$

The total columnar resistance R is obtained by integrating (5) between the Earth's surface and the high atmosphere. The plot of columnar resistance on May 24 is given in Figure 6. The value for the total columnar resistance of 24×10^{16} ohm-m² is obtained by assuming the contribution to R above 6 km is the same as that measured by *Woessner*, *Cobb*, and *Gunn* [1958] on a series of balloon flights in the Washington, D.C., area. It is to be noted that the low conductivity within both exchange layers is responsible for 85 pct of R. Between 3 and 6 km the measured conductivity and consequently the incremental columnar resistance are nearly the same as those observed over

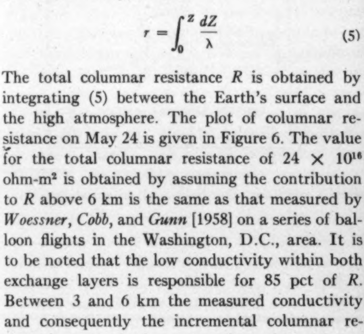

FIG. 6 – Columnar-resistance variation with altitude

Greenland [*Kraakevik*, 1958]. The fact that the columnar resistance over the Chesapeake Bay is more than three times that over Greenland explains the comparatively low value of conduction current at the former location.

The atmospheric potential is derived in two ways. First it is obtained directly by the numerical integration of the potential gradient. This method provides the true atmospheric potential V, which is plotted as a function of altitude in Figure 7. The potential at 6 km is 327 kv. If it is assumed that the exponential decrease in potential gradient between 3 and 6 km plotted in Figure 3 extends upward to the high atmosphere, the total atmospheric potential V_T is 341 kv. These values are considerably higher than the 220 kv 6-km potential and the extrapolated total potential of 283 kv obtained in Greenland by *Clark* [1957]. However, the Greenland potential was obtained at 11h 00m GMT, near the mean of the diurnal variation, and that in Figure 7 at 18h GMT, near the diurnal maximum. From the *Carnegie* 1928–29 ocean-surface potential-gradient results [*Torreson* and others, 1946], V_T at 18h GMT in May is 20 pct higher than that at 11h in September. Applying this correction to Figure 7, the total potential corresponding to 11h GMT for the May 24, 1956, sounding is 284 kv. The agreement between this value and V_T obtained in Greenland is excellent, both being considerably lower than the 360 kv value given by *Gish* [1951].

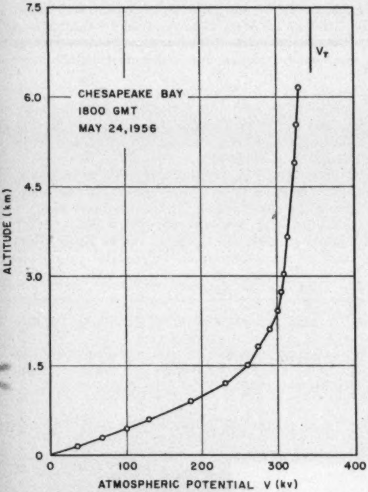

FIG. 7 – Atmospheric-potential variation with altitude

In the second (incorrect) method the atmospheric potential is derived from the average current density $\bar{j}$ and the columnar resistance r. In this case

$$V_j = -\bar{j}r \qquad (6)$$

and for the total potential

$$V_{jT} = -\bar{j}R \qquad (7)$$

Thus the curve in Figure 6, when multiplied by the average j over the 6-km altitude range, gives the variation in V_j with altitude. By way of comparison, V_j at 6 km is only 289 kv, where V is 327 kv. The reason for this discrepancy is that if the average current density of -1.29×10^{-12} amp/m^2 is assumed to be constant over this altitude range, $\bar{j}$ is less negative than the actual conduction current within the exchange layers, which contribute some 85 pct to R. Thus within the exchange layers V_j is too low, particularly at the top. The average current does not provide a compensating increase in V_j above the exchange layers because the contribution to R in this region is small. Another way of looking at it is that space-charge convection generates a current which is not negligible; hence a constant vertical conduction current density may not be validly assumed. If the current density measured at the lowest altitude were the surface value, and were assumed constant over the entire altitude range, then V_j at 6 km would be 411 kv, which is too high. Thus it is risky and in general incorrect to measure current density at one altitude (usually the surface) and compute a potential from an assumed constant current and a measured columnar resistance.

Eq. (7) provides the true potential only when the measured conduction current density is constant over the entire altitude range. In general, the incremental potential over a small altitude range is

$$dV = -j\,dR = -\frac{j}{\lambda}\,dZ = -E\,dZ \qquad (8)$$

and the true potential must be obtained from the measured electric field by integrating (8).

Summary and conclusions—An airplane was instrumented to measure simultaneously both polar conductivities, potential gradient, and several meteorological quantities, in order to study their variations in space and time. Representative altitude 'profiles' of conductivity and potential gradient over the Chesapeake Bay indicate the presence of a secondary exchange layer above the more common surface exchange layer. Above these layers, the total conductivity and the negative to positive conductivity ratio are in good agreement with results obtained previously in clean air over Greenland.

The computed conduction-current density profile over the Chesapeake Bay shows the effects of space-charge convection within the exchange layers. The conduction current density is substantially constant above these layers, having a magnitude of only 1.09 × 10^{-12} amp/m^2, but within the layers it is increased by some 40 pct due to a convection current. The space-charge density profile, derived from the potential-gradient distribution, is dominated by two regions of high positive concentration, one at the top of each exchange layer, near the bases of the associated temperature inversions. Low conductivity within the exchange layers is responsible for 85 pct of the extrapolated total columnar resistance of 24 × 10^{16} ohm m^2.

The extrapolated total atmospheric potential at 18h GMT, near the diurnal maximum, is 341 kv, based on a 6-km potential of 327 kv obtained by integrating the potential gradient. This is 20 pct higher than the total potential over Greenland at 11h GMT obtained previously, in excellent agreement with the average diurnal potential gradient variation measured by the *Carnegie*. The product of columnar resistance and current density, used by previous workers, provides erroneous values of atmospheric potential. These values are too high if the conduction current density near the Earth's surface is used, and too low if the current is averaged over the entire 6-km altitude range of measurement.

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The 27-day Period in United States Temperatures

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Abstract—The daily maximum temperature observations in the United States during two series of regular 27-day periods in the years 1947 and 1953 are harmonically analysed. The amplitude being statistically insufficient the reduced amplitude, that is amplitude divided by standard deviation, is introduced. The results arrived at are compared with those in Europe. The investigation discloses the intermediate action of the ionosphere, especially that of the magnetic storms in the F2 layer. We state the following sequence of phenomena in the 27-day period.

Solar activity	Year	Max. day	Magnetic storms F2 layer		Daily maximum temperature					
					Europe		United States			
							West		East	
			Max. day	Min. day	Highest day	Lowest day	Highest day	Lowest day	Highest day	Lowest day
High (R = 165)	1947	13.3	16.2	...	...	...	...	...	...	...
Weak (R = 13)	1953	13.6	...	17.9	...	...	...	...	...	...
High solar activity			...	...	...	21.0	...	22.2	26.9	...
Weak solar activity			...	...	...	19.2	...	22.3	24.9	...

The numerical results are shown in Tables 1 and 2.

This paper contains a comprehensive review of our communication [*Visser*, 1956] on the 27-day period, at the IUGG Assembly, Rome, 1954.

The method—When studying the 27-day period most investigators calculate average values over long time intervals. Yet this method is not quite acceptable because the periodicity is highly irregular: it starts at some unexpected moment, it dies out at another moment and it may be absent during long intervals. When average values are calculated over many years the period fades out or is revealed only poorly. For this reason we have confined our research to well developed regular occurrences of 27-day sunspot periods in which only one maximum and one minimum occur, returning in consecutive periods at about the same time. Such a case occurred during the summer of 1947. Eight well-developed 27-day periods were followed by significant heat waves in central Europe (see *The data* below). This fact led to an investigation of the daily maximum temperatures in Europe and North America. We shall discuss the results for the years 1947 and 1953.

When arranging the sunspot data in rows of 27 days the regularly recurring sunspot waves stand out and it is easy to select them. We have considered the central day of five consecutive days with highest relative sunspot numbers to be the epoch of the maximum.

Concerning the maximum temperatures we have calculated overlapping 27-day means and entered these means at the central day of the matching 27-day intervals. The differences between these mean values and those observed daily provide more or less regular successive positive and negative deviations, revealing the more or less regular occurrence of the period. We have arranged these temperature deviations in such a way that each of the sunspot maxima selected fell on the central day of the row of 27 temperature deviations. Thus we find the behavior of the temperature during 13 days before and 13 days after the sunspot maximum.

The result is accumulative. The influence of each individual sunspot period on the temperature may be weak, but by repeating the method for consecutive periods in quite the same way, the influence becomes more and more obvious when actually present. Therefore more or less periodical systems of 27 numbers are obtained. It is now necessary to test their significance.

For each series of selected recurrences the 27 daily averages both of the sunspot numbers and the maximum temperatures have been calculated and the results harmonically analysed. We have limited this research to the first harmonic. A random series of 27 numbers, however, when harmonically analysed, also may yield some phase angle ϕ, and some amplitude $\mathbf{a}$ and, therefore, we must check the reliability of the harmonics found. To this end we have determined for each of the 27 values obtained the difference observed minus harmonic and calculated the standard deviation σ. We must require that σ be small, or, better, that $\mathbf{a}/\sigma$ be large. This quotient is defined as the reduced amplitude $\mathbf{a}_r$. The reduced amplitude amounted to 4 or more for the sunspots, for the temperatures it was 1.5 and more.

Figure 1 shows the features of the method applied to 12 cases in the years 1947 and 1953.

Figures 1a and 1g show a very close relation between the sunspots and their harmonics both for the years 1947 and 1953. As to the other curves, for $\mathbf{a}_r = 1$ the limiting (dotted) curve reaches

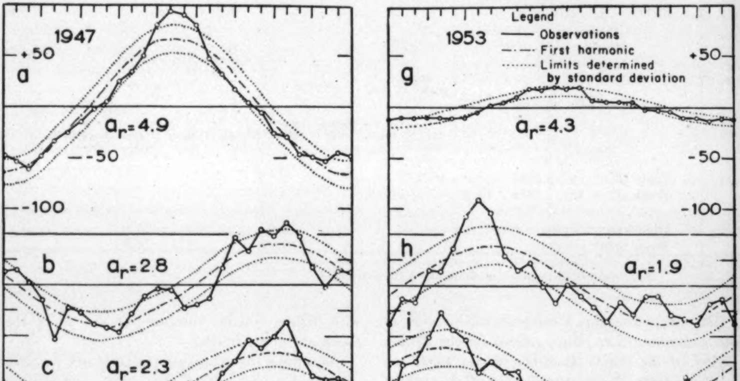

FIG. 1 – The 27-day period in 1947 (a to f): (a) sunspots; maximum daily temperatures at (b) Marburg, Germany; (c) De Bilt, The Netherlands; (d) Susanville, California; (e) Lakeview, Oregon; and (f) Newport, Vermont; 1953 (g to l): (g) sunspots; (h) I-index at De Bilt; maximum daily temperatures at (i) Green River, Utah; (j) Kassel-Harleshausen, Germany; (k) Lakeview, Oregon; and (l) Akron, Ohio; each scale division of the temperature curves represents 2° C, and of the I-index, 4 units; the abscissae represent the 27 days of the period.

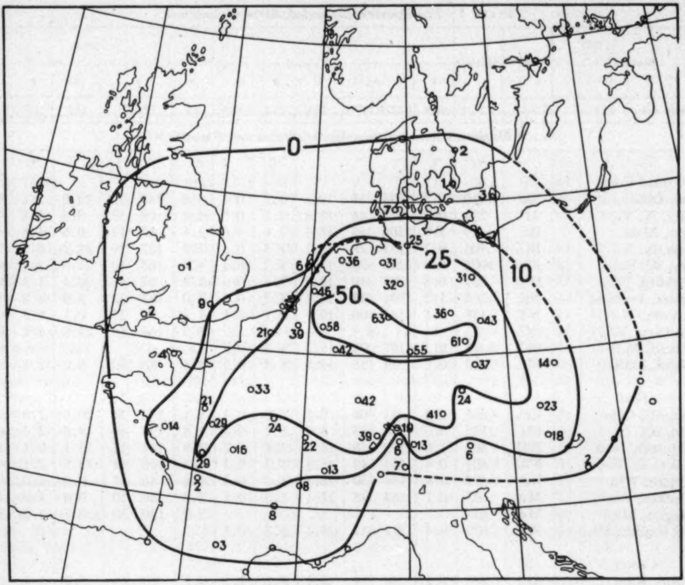

FIG. 2 – The heat waves in western Europe in 1947

the zero line, whereas for lower values of $\mathbf{a}_r$ it passes this line and the concordance between the observed data and the harmonics decreases rapidly. For $\mathbf{a}_r > 1$ the concordance may be considered to be sufficient. Yet, we have taken $\mathbf{a}_r = 0.8$ as the lowest reduced amplitude acceptable.

The curves reveal close connections with the sunspots, but in great variety. Compare Figure 1a with the others for 1947, and Figure 1g with the others of 1953.

The data—The sunspot maximum year 1947 showed a remarkably well-developed series of eight consecutive regular 27-day periods between April 14 and November 7 (rotation numbers 1559–1566 after Bartels's counting). These periods were followed by considerable heat waves over central Europe [*Visser*, 1949ab]. A rough survey over 45 years, 1910–1954, showed repeated occurrences of such cases [*Visser*, 1954]. Moreover, there were indications that the same effects, though on a smaller scale, were encountered in the United States [*Visser*, 1954]. These preliminary investigations induced a more exact study of the effects found.

The year 1953 was chosen because of the weak sunspot activity (one year before the minimum). This year contained a series of four regular sunspot waves, January 27–May 11 (Bartels's numbers 1637–1640). Notwithstanding the low solar activity, a periodic influence on the temperature, similar to that in 1947, (see Fig. 1) is evident.

Figure 2 shows the extent and intensity of the

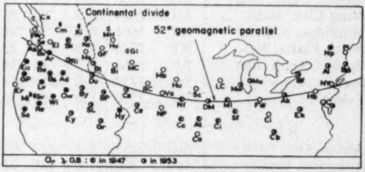

FIG. 3 – The stations in the United States of America and Canada

TABLE 1 – *Twenty-seven-day period; harmonic analyses*

Station	Symbol	Altitude	1947						1953					
			a	φ		D	σ	a_r	a	φ		D	σ	a_r
Sunspots	...	...	64.9	272°	16′	13.3	13.1	4.9	4.9	262°	32′	13.6	3.3	4.3
Maximum temperatures, United States and Canada														
		ft	°C	°	′		°C		°C	°	′		°C	
East Coast														
Akron, Ohio	Ak	1210	0.5	194	31	19.2	1.2	0.4	1.8	143	22	23.0	2.2	0.8
Albany, N. Y.	Al	292	0.9	212	44	17.8	1.7	0.5	1.4	78	32	0.8	1.8	0.8
Boston, Mass.	Bo	29	1.0	200	54	18.7	1.6	0.6	1.8	82	12	0.6	1.8	1.0
Buffalo, N. Y.	Bf	706	0.7	233	28	16.2	1.3	0.5	2.3	127	29	24.2	2.3	1.0
Elkins, W. Va.	Ek	2006	0.5	215	35	17.6	1.2	0.4	1.8	163	49	21.5	2.1	0.9
Harrisburg, Pa.	Hb	351	0.8	263	49	13.9	1.3	0.6	1.2	97	41	26.4	1.9	0.6
Newport, Vermont	Np	766	1.2	204	29	18.4	1.5	0.8	2.0	102	22	2.0	2.0	1.0
New York, N. Y.	NY	138	0.1	184	00	19.9	1.1	0.1	1.3	88	25	0.1	1.8	0.7
Ocean City, Md.	OC	25	...	...		...	...	...	0.9	144	59	22.8	1.1	0.8
Snowland, Md.	OC	25	0.2	187	08	19.7	1.2	0.2	...	...		...	...	...
Portland, Maine	Pl	63	0.8	229	53	16.5	1.4	0.6	1.3	88	50	0.0	2.1	0.6
East														
Cincinnati, Ohio	Ci	885	0.4	83	05	0.5	1.0	0.4	1.4	172	23	20.8	2.0	0.7
Corbin, Ky.	Cb	1175	0.5	38	35	3.8	1.2	0.4	1.8	193	48	19.3	2.3	0.8
Des Moines, Iowa	DM	800	1.0	102	58	26.0	1.4	0.7	2.9	114	42	25.4	2.5	1.2
Fort Wayne, Ind.	FW	801	0.4	131	49	23.8	1.2	0.3	1.4	136	14	23.5	2.1	0.7
La Crosse, Wis.	LC	672	0.4	156	50	22.1	1.3	0.3	1.4	86	47	0.2	2.0	0.7
Milwaukee, Wis.	Mw	693	0.7	164	36	21.4	1.5	0.5	2.2	89	10	0.0	1.9	1.2
Muskegon, Mich.	Mu	633	...	...		...	...	...	2.0	120	30	2.7	2.0	1.0
Grand Rapids, Mich.	Mu	689	0.4	111	11	25.4	1.2	0.3	...	...		...	...	...
Center														
Atchison, Kan.	At	973	1.2	48	51	3.2	1.1	1.1	0.7	20	46	5.2	2.7	0.3
Chanute, Kan.	Ca	977	0.5	37	59	3.9	1.1	0.5	1.1	0	26	6.7	2.0	0.6
Columbia, Mo.	Cl	785	1.0	70	49	1.4	1.2	0.8	0.1	200	54	18.7	2.8	0.0
Concordia, Kan.	Co	1392	1.2	59	12	2.3	1.4	0.9	1.1	41	34	3.6	2.8	0.4
Moline, Ill.	Ml	594	0.9	93	28	26.3	1.2	0.8	1.6	100	49	26.2	2.4	0.7
Norfolk, Neb.	Nf	1544	1.2	80	44	0.7	1.5	0.8	0.5	39	22	3.8	2.8	0.2
Springfield, Ill.	Sf	636	1.4	78	28	0.8	1.1	1.3	0.8	156	18	22.0	2.3	0.4
East-West														
Billings, Mont.	Bi	3568	0.6	55	44	2.6	1.3	0.5	1.8	319	17	9.8	2.7	0.7
Butte, Mont.	Bt	5533	0.8	11	22	5.9	1.3	0.6	2.4	328	52	9.1	2.4	1.0
Casper, Wyo.	Cs	5290	1.0	110	40	25.4	1.5	0.7	2.9	343	09	8.0	3.0	1.0
Cheyenne, Wyo.	Ce	6139	1.1	81	38	0.6	1.8	0.6	2.7	331	03	8.9	3.1	0.9
Glasgow, Mont.	Gl	2086	0.6	112	39	25.3	1.5	0.4	...	...		...	...	...
Great Falls, Mont.	GF	3664	0.3	43	57	3.4	1.4	0.2	1.6	303	24	11.0	2.8	0.6
Havre, Mont.	Hv	2488	0.6	62	51	2.0	1.2	0.5	0.5	285	57	12.3	2.7	0.2
Huron, S. Dak.	Hu	1289	0.6	68	17	1.5	1.5	0.4	1.8	21	48	5.1	2.9	0.6
Medicine Hat, Alta.	MH	2365	0.4	21	15	5.2	3.6	0.1	...	...		...	...	...
Miles City, Mont.	MC	2629	0.8	67	48	1.6	1.3	0.6	1.3	335	22	8.6	2.7	0.5
Mobridge, S. Dak.	Mb	1664	0.4	27	41	4.6	1.7	0.3	1.5	10	39	5.9	3.1	0.5
North Platte, Neb.	NP	2783	0.8	70	12	1.5	1.6	0.5	1.4	329	07	9.1	2.8	0.5
Rapid City, S. Dak.	RC	3165	0.7	44	16	3.6	1.6	0.4	1.6	12	44	5.8	2.9	0.6
Spencer, Iowa	Sc	1339	0.9	116	13	25.0	1.5	0.6	1.2	68	17	1.6	2.6	0.5
Valentine, Neb.	Va	2598	1.0	63	39	2.0	1.7	0.6	0.6	4	14	6.4	1.5	0.4
West														
Adrian, Ore.	Ad	2235	1.3	327	06	9.2	1.0	1.3	2.0	343	29	8.0	1.9	1.0
Arlington, Ore.	Ar	350	1.0	338	57	8.3	1.0	1.0	0.9	330	22	9.0	0.7	1.3
Bend, Ore.	Be	3599	1.7	331	25	8.9	1.3	1.3	2.6	307	09	10.7	2.3	1.1
Big Piney, Wyo.	BP	6820	0.5	45	58	3.3	1.1	0.5	3.0	322	10	9.6	2.1	1.4
Bonneville, Ore.	Bv	851	0.9	2	44	6.5	1.3	0.7	1.1	313	45	10.2	1.5	0.7

TABLE 1 – *Continued*

Station	Symbol	Altitude	1947						1953					
			$\mathbf{a}$	ϕ		D	σ	$\mathbf{a}_r$	$\mathbf{a}$	ϕ		D	σ	$\mathbf{a}_r$
Sunspots	...	...	64.9	272°16′		13.3	13.1	4.9	4.9	262°32′		13.6	3.3	4.3
Maximum temperatures, United States and Canada (*Continued*)														
		ft	°C	°	′		°C		°C	°	′		°C	
Burley, Idaho	By	4149	0.7	325	00	9.4	1.2	0.6	2.8	338	47	8.3	2.4	1.1
Burns, Ore.	Bs	3947	1.5	337	20	8.4	1.4	1.1	2.9	341	46	8.1	2.2	1.3
Carmi, B. C.	Cm	4048	1.1	341	30	8.7	1.3	0.8	...	...		...	...	...
Comox, B. C.	Cx	75	0.4	14	18	5.6	0.8	0.5	...	...		...	...	...
Dubois, Idaho	Du	5152	0.3	306	08	10.7	1.0	0.3	2.2	353	57	7.2	1.8	1.2
Ellensburg, Wash.	El	1727	0.7	338	21	8.4	1.0	0.7	1.0	359	41	6.8	1.6	0.0
Ely, Nev.	Ey	6262	0.8	319	32	9.8	1.3	0.6	3.3	340	27	8.2	2.3	1.4
Eugene, Ore.	Eu	364	1.0	343	24	8.0	1.3	0.8	1.4	320	41	9.7	1.4	1.0
Eureka, Calif.	Er	43	0.4	42	58	3.6	0.7	0.6	0.3	298	27	11.3	0.8	0.4
Grant's Pass, Ore.	GP	926	1.1	319	08	9.8	1.4	0.8	2.2	314	13	10.2	1.4	1.6
Green River, Utah	Gr	4087	0.4	357	18	7.0	0.8	0.5	2.9	345	47	7.8	1.5	1.9
Hayden, Colo.	Hy	6337	1.1	48	22	3.1	1.4	0.8	2.5	330	06	9.0	2.3	1.1
Kalispell, Mont.	Ka	2956	0.6	0	19	6.7	1.1	0.5	1.5	321	23	9.6	1.8	0.8
Kimberley, B. C.	Ki	3016	0.9	329	02	9.1	0.9	1.0	...	...		...	...	...
Lakeview, Ore.	Lv	4765	1.6	319	44	9.8	1.4	1.1	2.8	329	30	9.0	2.3	1.2
Missoula, Mont.	Ms	3201	0.8	342	06	8.1	1.2	0.7	1.2	346	40	7.8	2.2	0.5
Owyhee, Nev.	Ow	5396	1.2	309	06	10.6	1.3	0.9	3.3	341	10	8.1	2.4	1.4
Reno, Nev.	Re	4406	2.0	323	57	9.4	1.3	1.4	2.8	344	55	7.9	2.0	1.4
Riggins, Idaho	Ri	1685	0.7	328	36	9.1	1.0	0.7	1.9	328	14	9.1	2.0	1.0
Sacramento, Calif.	Sa	25	1.8	335	35	8.6	1.3	1.4	1.2	317	45	10.0	1.4	0.9
Salt Lake City, Utah	SL	4222	0.8	272	35	13.4	1.3	0.6	3.1	339	40	8.3	2.3	1.4
Spokane, Wash.	Sk	2357	1.2	337	54	8.4	1.3	0.9	1.2	339	59	8.2	1.8	0.7
Susanville, Calif.	Su	4152	2.2	316	54	10.0	1.3	1.7	...	...		...	...	...
Mineral, Calif.	Mi	4850	...	...		...	...	...	3.3	328	19	8.1	2.2	1.5
Winnemucca, Nev.	Wi	4288	1.4	321	34	9.7	1.3	1.1	3.0	347	50	7.7	2.3	1.3
West Coast														
Astoria, Ore.	As	220	0.2	8	44	6.1	1.1	0.2	0.2	296	45	11.5	1.2	0.2
Port Angeles, Wash.	PA	15	0.4	337	16	8.4	1.1	0.4	0.3	323	01	9.5	1.1	0.3
Seattle, Wash.	Se	388	0.3	345	51	7.8	0.9	0.3	0.3	325	17	9.4	1.7	0.2
Europe														
De Bilt, Neth.	DB		2.7	172	55	20.8	1.2	2.3	1.7	16	14	5.5	1.3	1.3
Den Helder, Neth.	DH		0.8	179	15	20.3	1.2	0.7	0.4	34	34	4.2	1.1	0.4
Marburg, Germ.	M		3.2	165	26	21.3	1.1	2.8	...	...		...	...	...
Kassel-Harlesh. Germ.	K		...	...		...	...	...	2.7	11	31	5.9	1.6	1.7
Ionosphere; F2 storms														
Slough F2, Gr. Br.	S		0.5	250	09	15.0	0.6	0.8	...	...		...	...	...
Washington F2, D. C.	W		3.6	217	45	17.4	2.7	1.4	6.0	29	45	4.5	4.0	1.5
De Bilt I, Neth.	DB		...	...		...	...	...	6.0	34	04	4.2	3.1	1.9

$\mathbf{a}$ = harmonic amplitude; θ = phase angle; D = maximum day; σ = standard deviation; $\mathbf{a}_r$ = reduced amplitude.

1947 series at 69 stations in western Europe [*Visser*, 1954]. The intensity has been characterized for each wave at each station by a scale of 1 to 6, 1 for amplitudes generally more than 3°C below the average value, 6 for amplitudes generally more than 3°C above. The sum of these values is considered to represent the total intensity of the phenomenon. Maximal intensity (sums above 50) occurs in central Europe (Maastricht, 58; Marburg, 63; Bad Kissingen, 55; Fichtelberg, 61).

Figure 3 presents the stations in the United States and Canada which have been studied. The reduced amplitudes have been marked by open circles, for all values of $\mathbf{a}_r$ equaling or exceeding 0.8 being indicated by filling in half of these circles, the left half representing 1947, the right

1953. Table 1 provides a key to the stations and other pertinent information.

Certain characteristic differences have been noted. In the eastern states 1953 is the more outstanding (to Milwaukee, Mw), in the central states 1947. Along the continental divide is an area in which 1953 stands out. In the western states the connection is well developed in both years, with the exception of the coastal stations which do not show clear connections in either year.

We have divided the United States into six areas (see Table 1) in the East, East Coast, East, and Center; in the West, transition zone East-West, West, and West Coast. It was not always possible to fix the limits between these areas exactly, so we have referred the periodic characteristics to the geographical positions. Thus, for example, Akron, Ohio, and Elkins, West Virginia, are shown in the East Coast stations, though they are over 200 mi inland.

Regarding the 52° circle of geomagnetic latitude (Fig. 3), see *The ionosphere* below.

More particulars are to be found in Figure 4 for the northwestern states and Canada for 1947 and 1953, respectively. On these maps the intensity has been expressed in the reduced amplitude; the numbers inscribed at each station indicate the average maximum day. Figures 2 (Europe) and 4 (western United States and Canada) show similar features, a central area with high intensity decreasing toward the coasts and inland.

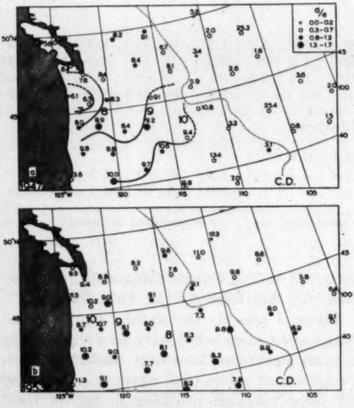

FIG. 4 – The 27-day period in western United States and Canada, 1947 and 1953

In 1947 a propagation in the western area from northwest to southeast is obvious, the maximum taking from Day 7 to Day 10 to cross the country. The data exhibit an abrupt change of phase east of the continental divide. It is impossible simply to extend the isochrons to the eastern area. One is inclined to consider the continental divide as a barrier to the propagation. Two stations, however, situated at the west side (Big Piney, Wyoming, and Hayden, Colorado), behave in a manner similar to those in the east, perhaps because of some orographical influence.

In 1953 west of the continental divide the maxima arrive on the same days as in 1947, but the propagation is from east to west (Days 8 to 10). Moreover the continental divide does not act as a barrier; on both sides we note that the maximum days are the same.

The reduced amplitude—The systematic differences in $\mathbf{a}_r$ between the two years 1947 and 1953 are demonstrated in Figures 5 and 6. The $\mathbf{a}_r$ values for 1947 are the abscissae, those for 1953, the ordinates. The limiting value $\mathbf{a}_r = 0.8$ is indicated by vertical and horizontal lines. The six areas adopted have been marked by different symbols.

At a glance we see the opposite behavior of the two years in the eastern areas (Fig. 5), whereas in the West (Fig. 6) the two years behave in the same way. In particular we do not find stations in the upper right-hand square of Figure 5 and only one (Spokane, Washington) in the lower right-hand part of Figure 6.

The East and East Coast stations show a well-developed periodicity in 1953 in contrast to 1947; the central stations, all of them around about 95° W, on the other hand, had a strong periodicity in 1947, a weak one in 1953.

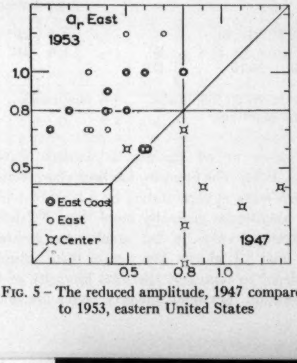

FIG. 5 – The reduced amplitude, 1947 compared to 1953, eastern United States

Figure 6 shows the period to be poorly developed in both years at the three West Coast stations, positive correlations in both years at the West stations, all of them situated on the west side of the continental divide. In the area of the East-West stations (the transition zone between the continental divide and the Central stations) the periodicity as a rule is poorly developed in both years.

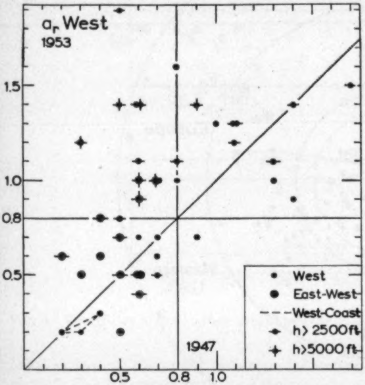

FIG. 6 – The reduced amplitude 1947 compared to 1953, western United States

It is possible to study the influence of the height above sea level h in the western areas. The stations with altitudes ranging from 2500 ft up to 5000 ft generally behave in a manner similar to lower ones. Without exception stations above 5000 ft experienced a stronger periodicity in 1953 than in 1947.

The results—The complete results of the investigation are represented in the clock diagrams, Figure 7 for 1947 and Figure 8 for 1953. The 27 days of the period have been arranged as the figures of the clock's face and the stations have been plotted by means of the maximum day and the reduced amplitude as polar coordinates. Here again the limit of $a_r = 0.8$ has been indicated. In these figures some other phenomena have been introduced, which will be discussed below.

As a consequence of the method used we find the sunspot maximum at Day 13.5; its reduced amplitude lies far outside the limits of the figures.

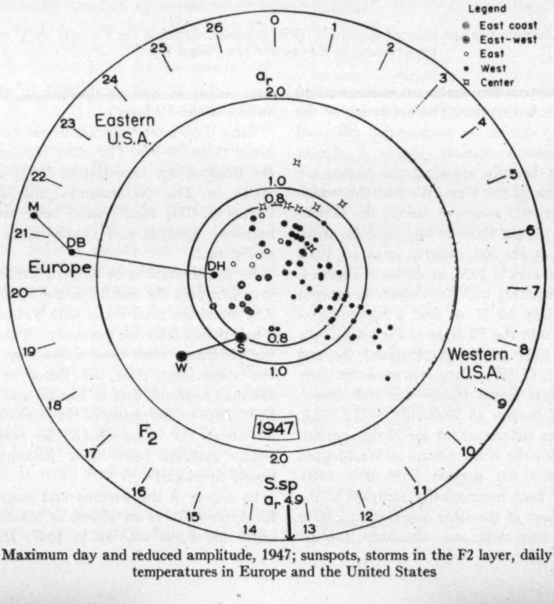

FIG. 7 – Maximum day and reduced amplitude, 1947; sunspots, storms in the F2 layer, daily maximum temperatures in Europe and the United States

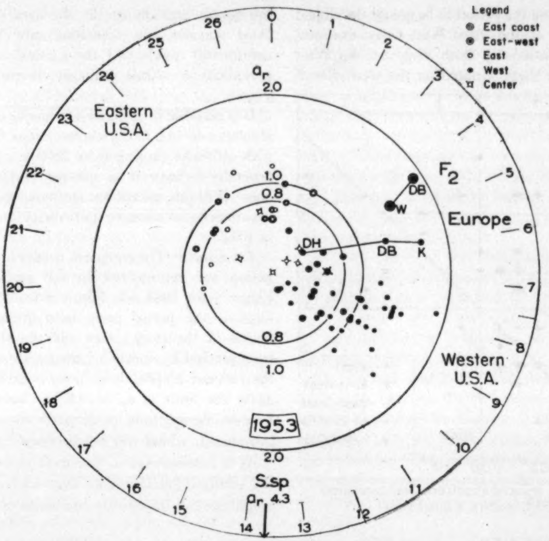

Fig. 8 – Maximum day and reduced amplitude, 1953; sunspots, storms in the F2 layer, daily maximum temperatures in Europe and the United States

We see the western stations accumulating around about Day 9 in both years. The scattering of the points is wholly due to the propagation discussed above. The eastern stations display a greater scattering, but broadly speaking the phases are opposite to those of the West. We find the transition stations in 1947 scattered among the eastern ones; in 1953 among those of the western areas. They behave as do the eastern areas in 1947, like the western area in 1953, as shown in Figure 4.

In Figure 7 starting with the maximum sunspot Day 13.5, at Day 16–17 we find a maximum of magnetic storms in the F2 layer of the ionosphere. The F2 data refer to Slough, England (S) and Washington, D. C. (W). They represent the daily number of storm hours [*Radio Research Board*, 1947; *National Bureau of Standards*, 1947; 1953]. They have been calculated for six 27-day periods only, 1561–1566, the observations in Washington being incomplete for periods 1559 and 1560. The data have been harmonically analysed in the same way as those of the other observations. Both stations agree very well, and, obviously, the 27-day period is well established in the magnetic storms of the F2 layer.

Some days later temperature maxima in Europe occur (Day 20–21). The three stations plotted in the diagram are Den Helder (DH) and De Bilt (DB) in The Netherlands, and Marburg in Germany. The results have been arrived at by harmonic analysis and closely agree with those of Figure 2.

As to the stations of western United States we may interpret the results of the figure as follows. The minimum must occur with a time interval of a half period after the maximum. This means that the minimum must present itself at Day 22–23, two days later than the European maximum. We may conclude that in Europe and the western United States the phases of the period are opposite. At about the same epoch the eastern United States stations have their maximum, though poorly developed.

In Figure 8 the western and eastern areas of the United States are shown to behave in 1953 in quite the same way as in 1947. However, the

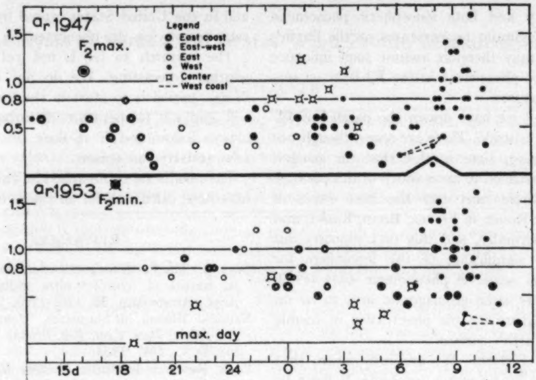

Fig. 9 – The 27-day period in the United States and Canada, maximum day and reduced amplitude, 1947 and 1953.

behavior in the F2 layer and in Europe are contrary to 1947. The F2 storms experience their maximum value at Day 4 and have, therefore, their minimum at Day 18. The two F2 points in the diagram represent the daily amount of storm hours in Washington (as in 1947) and the I-index in De Bilt (see also Fig. 1h). Again, there is a good agreement, and the period is in the ionosphere well developed.

In 1953 as in 1947 European temperature maxima follow the F2-storm maxima (Den Helder and De Bilt, as before, and Kassel-Harleshausen (K) in Germany) at Day 5. Their minimum occurs at Day 19.

Figure 9, finally, represents the features in two rectangular diagrams, the maximum days as abscissae, the reduced amplitudes as ordinates. Only the average F2 figures have been plotted in these diagrams. This figure presents some of the features more clearly than do the clock diagrams. For example, the weak development and the broad scattering of the central stations is well established. The moving of the East-West maxima from Day 26–7 in 1947 to Day 5–12 in 1953 is clear. We point to a similar moving of the East-Coast maxima from Day 16–20 in 1947 to Day 21–2 in 1953. However, especially in 1947, the intensity is small and probably statistically insignificant.

The ionosphere—In the previous section we have found indications of a possible link between the

Table 2 – *Results of study*

Item	1947	1953
Solar activity	high	weak
Rotation	1559–1566	1637–1640
Average R	165	13
Amplitude **a**	64.9	14.9
Standard deviation σ	13.1	3.5
Reduced amplitude $\mathbf{a}_r$	4.5	4.3
Maximum day	13.3	13.6
F2 storms, number of observations	$n = 2$	$n = 2$
Amplitude **a**	2.0	6.0
Standard deviation σ	1.7	3.6
Reduced amplitude $\mathbf{a}_r$	1.1	1.7
Maximum day	16.2	4.4
Minimum day	. . .	17.9
Daily maximum temperature (Celsius degrees)		
Europe, number of observations	$n = 2$	$n = 2$
Amplitude **a**, °C	3.0	2.2
Standard deviation σ, °C	1.2	1.4
Reduced amplitude $\mathbf{a}_r$	2.6	1.5
Maximum day	21.0	5.7
Minimum day	. . .	19.2
Western U.S.A. (West)	$n = 16$	$n = 21$
Amplitude **a**, °C	1.4	2.5
Standard deviation σ °C	1.3	1.9
Reduced amplitude $\mathbf{a}_r$	1.1	1.3
Maximum day	8.7	8.8
Minimum day	22.2	22.3
Eastern U.S.A.	$n = 7$	$n = 11$
Amplitude **a**, °C	1.2	1.9
Standard deviation σ, °C	1.3	2.0
Reduced amplitude $\mathbf{a}_r$	0.9	1.0
Maximum day	(26.9)	(24.9)

solar activity and both ionospheric phenomena and daily maximum temperatures on the Earth's surface. We may therefore assume some influence of the electric phenomena in the F2 layer on sea-level temperatures.

In Figure 3 we have drawn the parallel of 52° geomagnetic latitude. There are some, though not very convincing, signs in this that the sunspot influence is confined to areas south of this parallel. This same circle runs over the heat waves of Europe, over Rouen in France, Bonn, Kassel, and Dessau in Germany, and this fact supports our view of the significance of the ionosphere for meteorological sea-level phenomena. *Clay* [1932] has found this same geomagnetic area to be an important feature for the penetration of cosmic rays to the Earth's surface.

Concluding remarks—We are fully aware that this survey is by no means complete. It must be extended over a greater part of North America and elsewhere, but the results are so characteristic that it seems worth while to investigate these matters thoroughly.

We do not speak of the explanation. We do not know enough of the circumstances either at the solar surface, or in the ionosphere, or even in the troposphere, to enable us to discuss the theoretical fundamentals of the phenomena disclosed in this paper.

Since the maximum temperature depends upon the general atmospheric circulation an intensive study of the synoptic situation should follow. On this side of the problem *Rodewald* [1955–1956] has made important contributions. It is now a well established fact that seasonal effects are active, but the data available are still insufficient to deduce them. I should like to point to the possibility of some blocking action in western Europe and in the United States caused by the effects of solar activity on the phenomena in the F2 region.

The research so far is not yet applicable to weather forecasting. We do not know when a 27-day period is to start in the Sun nor when it will end. A temperature disturbance does not always follow and if it does, it depends upon solar activity and season.

The results are summarized in Table 2 (averages have been calculated for all values of $\mathbf{a}_r > 0.8$).

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An Analysis of Some Over-Water Wind Profile Measurements

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Abstract—For several days during the spring of 1955, wind-speed profiles were measured from an oil drilling platform in the Gulf of Mexico. Various standard parameters such as the friction velocity, roughness parameter, surface stress, and resistance coefficient are computed from these profiles. Functional relationships are derived between the various computed parameters and the wind speed at ten meters. A re-analysis of data obtained by Wüst in 1919 shows that it is in very good agreement with the present data.

An attempt is made to relate the roughness parameter with the root-mean-square of the water-level fluctuations, and though some indication of a dependence can be inferred, there is too much scatter of the plotted points to arrive at a unique functional relationship.

Introduction—During the period April 19 to May 2, 1955 meteorological and oceanographic measurements and observations were taken in conjunction with field measurements of the over-water propagation of microwave frequency electromagnetic waves at low elevation angles. Although a wide variety of interesting data were obtained [*Wagner* and *Gerhardt*, 1957] only the wind-profile analysis will be discussed in this paper.

The site of the meteorological observations was an oil drilling platform in the Eugene Island area of the Gulf of Mexico, off the coast near Morgan City, Louisiana. The platform is about 30 mi from the mainland and stands in about 35 ft of water. The top of the platform is 32 ft above mean low water.

Instrumentation and observations—A light triangular aluminum tower mounted on the southeast corner of the platform served as a support for three 3-cup dc anemometers at 2.8, 7.2, and 13.0 meters above mean low water. Three-foot booms were employed in removing the anemometers from the immediate vicinity of the tower and platform. With the platform oriented exactly north-south, this installation permitted the measurement of undisturbed air flow for wind directions from approximately north clockwise through southwest. The anemometer output was recorded on Esterline-Angus strip-chart recorders having a full scale calibration of 0 to 50 mi/hr.

Because the meteorological observations were coordinated quite closely with the radio data runs, the wind data consisted of five and ten minute samples of the wind speed. Only the ten minute wind-speed samples are used in this analysis. In comparing these ten-minute mean wind profiles with one another, quite large variations were occasionally found in the measured wind speed between runs taken only a few minutes apart. For this reason it was decided that the ten-minute averaging time was too short to obtain a representative mean wind profile. Instead, each day was arbitrarily divided into three time periods, and all of the ten-minute profiles falling within each of these time periods were averaged. Thus, each day consists of: (1) a mean morning profile consisting of all ten-minute profiles taken between about 06h 00m and 10h 00m; (2) a mean midday profile consisting of all ten-minute profiles taken between 10h 00m and 14h 00m, and, (3) a mean afternoon profile which consists of all ten-minute runs taken between 14h 00m and about 20h 00m (all CST). Each time period contains about 50 minutes (five samples) of data. All of the ten-minute runs for each day were also averaged in order to obtain a mean daily wind profile.

Plotting the profiles—When wind profile observations are made over-land, the anemometer height is designated as the height of the instrument above the surface of the ground. When dealing with mean profiles over water it is often quite difficult to say exactly how high the anemometers are above the water surface. The anemometers during these experiments were at a fixed height above the mean low-water level, thus there was a variable distance between the actual water surface and the anemometers not only because of variable wind wave and swell heights, but also because of tidal fluctuations.

In an effort to minimize this difficulty, the mean water level during each time period and each day was computed from the theoretical tide data for Ship Shoal Lighthouse, which is located about 20 mi to the east of the observation platform. These computed values were used for the mean height of the water surface for each time period and daily mean wind speed profile, respectively. Using this height correction factor, the mean profiles are

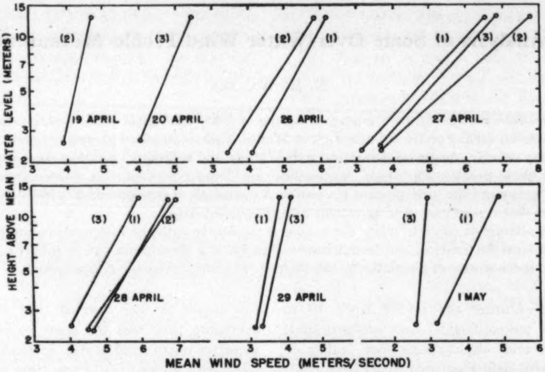

FIG. 1 – Mean wind-speed profiles for the time periods: (1) 06h 00m to 10h 00m, (2) 10h 00m to 14h 00m, and (3) 14h 00m to 20h 00m (all CST)

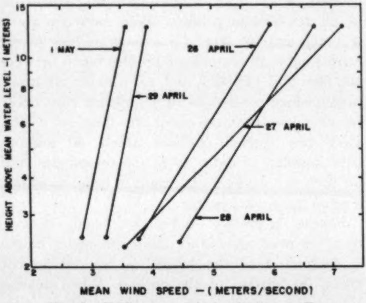

FIG. 2 – Daily mean wind velocity profiles

plotted with a logarithmic height scale in Figures 1 and 2.

On the last day of data collection, the anemometer at the middle level (7.2 m) was found to be indicating a wind speed which was much too low. On some occasions the cups would stop completely, while the anemometers at the other two levels remained in motion. An inspection of the instrument showed that friction tape, which was used to hold the electrical leads in place, had become lose and was becoming lodged between the stationary portion of the anemometer and the rotating weather shield.

Examination of all data from the middle anemometer made it appear likely that this condition had been present, but unnoticed, for some time. Thus, in Figures 1 and 2 and the following analysis the middle anemometer data have been omitted and a strict logarithmic (neutral stability) wind profile is assumed. On the basis of computed Richardson numbers this appears to be quite a valid assumption.

Computations from the profiles—In order to compare these data with the results obtained by others, various standard parameters may be computed from the mean wind profiles. Having assumed a logarithmic wind profile defined by the upper and lower mean wind speeds, the roughness parameter z_0 and the friction velocity U_* are found by determining the zero wind intercept and the slope of the profile, respectively. From the resulting values of the friction velocity, values for the surface stress τ are computed from the formula

$$\tau = U_*^2 \rho \tag{1}$$

where ρ is the air density.

Values for the resistance coefficient are also computed. The resistance coefficient γ^2 is a dimensionless parameter defined by *Taylor* [1916] as

$$\gamma^2 = \frac{\tau}{\rho U^2} = \frac{U_*^2}{U^2} \tag{2}$$

In order to be consistent with previous determinations of this parameter, the interpolated ten-meter mean wind speed is used for U.

The Richardson number, defined by

$$Ri = \frac{(g/T)((\partial T/\partial z) + \Gamma)}{(\partial U/\partial z)^2} \tag{3}$$

is computed for each time period when data permitted. In (3) T is the absolute temperature, g is the acceleration of gravity, and Γ is the adiabatic lapse rate. The vertical gradients of temperature are computed from the psychrograph sounding levels of zero and 25 ft below the top of the platform, and the wind gradient from the lower and upper mean wind speeds.

Discussion of the data—The relationship between the shape of the wind profile and the Richardson number has been discussed by *Deacon* [1949]. For our assumption of a semi-logarithmic relationship between wind speed and height to be considered valid it must be shown that the atmosphere was adiabatically stratified during periods of data collection. ***Neumann*** [1956] has stated that normally the atmosphere is in neutral equilibrium over large bodies of water. Computations of the Richardson number from (3) give additional verification to Neumann's statement. These values are given in Table 1. It may be seen from these data that the computed Richardson numbers show an essentially adiabatically stratified atmosphere.

A very wide range of values was found for the roughness parameter. The smallest value of 5×10^{-4} centimeters occurred during the third time period on May 1 and the largest value of 51 centimeters during the second time period on April 27. An examination of the literature gives little support for the larger magnitudes obtained in this analysis. Some of the better known values for the roughness parameter as obtained over a water surface are summarized in Table 2.

TABLE 1 – *Computed values for the Richardson number*

Date	Time period	Richardson number
1955		
April 19	2	No temperature data
20	3	−0.005
26	1	−0.013
	2	−0.009
27	1	0.003
	2	−0.001
	3	−0.001
28	1	No temperature data
	2	0.013
	3	0.009
29	1	0.018
	3	0.011
May 1	1	0.013
	3	No temperature data
April 26	Mean	−0.001
27	Mean	0.000
28	Mean	0.011
29	Mean	0.014

TABLE 2 – *The roughness parameter over water as determined by various investigators*

Investigator	z_0	Dependence on wind speed
	cm	
Rossby and *Montgomery* [1936]	0.6	6.5 m/s at 6 m
Model [1942]	0.07	Independent of wind speed
Deacon [1953]	0.02 to 0.04	7.5 m/s at 15 m
Hay [1955a]	0.02 to 0.25	Linear dependence on 2 m wind speed from 5 to 9 m/s
Present analysis	0.0005 to 51.0	An approximately semi-logarithmic dependence on 10 m wind speed from 3 to 7 m/s

Plots of the interpolated wind velocity at ten meters against the friction velocity and the roughness parameter are shown in Figures 3 and 4 respectively. The general trend of these two graphs is intuitively satisfying; that is, as the ten-meter wind speed increases, the friction velocity and the roughness parameter increase. This implies that the configuration of the water surface is largely dependent on the wind speed and that with increasing wind velocities there occurs an increase in the roughness characteristics of the water surface and an increase in the stress at the air-water boundary.

The solid lines on Figures 3 and 4 represent the straight lines of best fit (by eye) for the plotted data. The equations for these lines (in cgs units) are, from Figure 3

$$\ln U_{10} = 0.369 \ln U_* + 4.868 \tag{4}$$

and from Figure 4

$$\ln z_0 = 0.023 \ U_{10} - 11.086 \tag{5}$$

The logarithmic wind profile is normally given by the formula

$$U = \frac{U_*}{k} \ln \frac{z}{z_0} \tag{6}$$

where k is von Karman's constant (assumed equal to 0.400). If we let U represent the wind speed at ten meters then (6) may be written

$$U_{10} = \frac{U_*}{k} (3 \ln 10 - \ln z_0) \tag{7}$$

Eq. (7) and all of the ensuing development will be in cgs units.

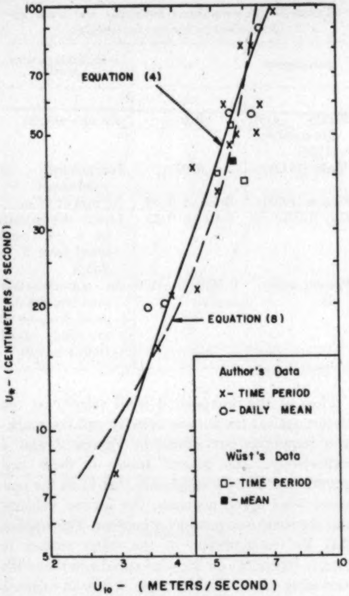

FIG. 3 – The friction velocity plotted against the ten-meter wind speed

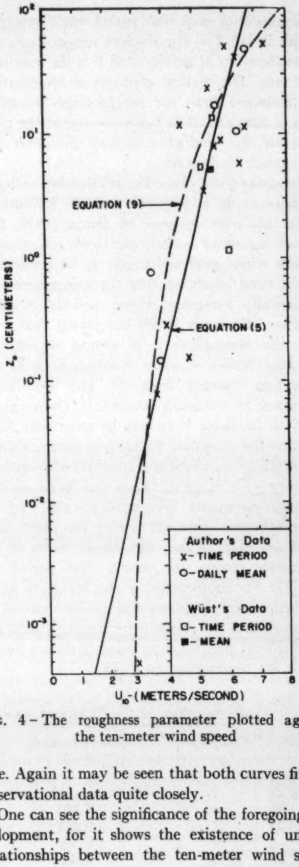

FIG. 4 – The roughness parameter plotted against the ten-meter wind speed

Theoretically, if (4) and (5) accurately represent the data, then by substituting (4) into (7) one should obtain (5). Likewise, by substituting (5) into (7) one should obtain (4). Substitution for ln z_0 from (5) into (7) and solving for U_{10} gives

$$U_{10} = \frac{17.994\ U_*}{0.400 + 0.023\ U_*} \tag{8}$$

Eq. (8) is plotted as a dashed line in Figure 3. Both the estimated and semi-empirically derived curves are quite close together and each curve adequately describes the data.

The same procedure can be followed to obtain a second equation relating the roughness parameter and the ten-meter wind speed. Substitution for U_* from (4) into (7) and a rearrangement of terms gives

$$\ln U_{10} = 0.585\ \{12.276 - \ln (6.908 - \ln z_0)\} \tag{9}$$

Eq. (9) has been plotted on Figure 4 as a dashed line. Again it may be seen that both curves fit the observational data quite closely.

One can see the significance of the foregoing development, for it shows the existence of unique relationships between the ten-meter wind speed and the friction velocity, and the ten-meter wind speed and the roughness parameter. By measuring only the ten-meter wind speed (U_{10}) the friction velocity and roughness parameter can be determined either by a simple computation involving (4), (5), (8), or (9) or by employing Figures 3 and 4.

Figure 5 shows the friction velocity plotted against the roughness parameter. Elimination of U_{10} by combining (5) and (4) yields

$$\ln U_* = 2.710 \ln (\ln z_0 + 11.086) - 2.967 \tag{10}$$

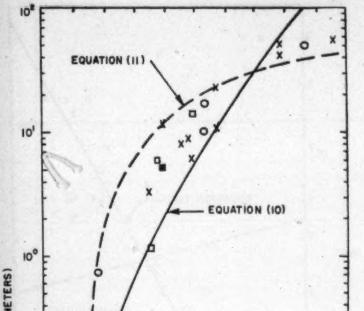

FIG. 5 – The roughness parameter plotted against the friction velocity

This equation is plotted as a solid curve in Figure 5. A second relationship may be derived between U_* and z_0 by combining (8) and (9). This gives

$$\ln \frac{U_*}{0.400 + 0.023\, U_*}$$

$$= 0.585\,\{12.276 - \ln(6.908 - \ln z_0)\} - 2.890 = f(z_0)$$

and solving for U_*

$$U_* = \frac{0.400 \exp[f(z_0)]}{1 - 0.023 \exp[f(z_0)]} \tag{11}$$

Eq. (11) is plotted as a dashed curve in Figure 5. As one would expect, (10) and (11) both accurately describe the data given in Figure 5.

In an attempt to find independent data which would help to verify the relationships shown in Figures 3, 4, and 5 the author re-analyzed Wüst's data (as given in *Rossby* and *Montgomery* [1936]). In order to be consistent in the method of analysis, Wüst's wind data for one and six meters above the water surface were reduced to time period mean wind speed profiles as shown in Table 3.

Also indicated in Table 3 are mean values for the various parameters determined by averaging the values for $\bar{U}_6$ and $\bar{U}_1$ for time periods 1, 2, and 3. Values for the ten-meter wind speed were found by assuming adiabatic conditions and extending the profile up to the ten-meter level.

The resulting values for the roughness parameter, friction velocity and ten-meter wind speed can then be plotted on Figures 3, 4, and 5. Examination of these figures shows that Wüst's data agrees well with the author's data.

Figure 6 is a replot of the data given in Figure 3. The surface stress is proportional to the square of the friction velocity as shown by (1), therefore in Figure 6 the stress is plotted against the square of the wind velocity at ten meters. The equation for the straight line of best fit may be determined as follows: Squaring both sides of (4), assuming an air density value of 1.25×10^{-3} gm/cm³, and employing the relationship given by (1) yields

$$\ln U_{10}^2 = 0.369 \ln \tau + 12.227 \tag{12}$$

The dashed curve in Figure 6 represents stress data obtained by *Moore* and *Laird* [1957] in a wind tunnel using a stationary mechanical wave boundary. There is an apparent divergence of the two sets of data in the high wind speed region, however, because of the differences between the two systems employed for analysis the agreement is considered to be quite good.

Figure 7 shows the variation of the resistance coefficient with the square of the wind velocity at ten meters. The equation for the straight line of best fit is

$$\ln U_{10}^2 = 0.544 \ln \gamma^2 + 12.766 \tag{13}$$

TABLE 3 – *A re-analysis of Wüst's over-water wind data*

Time period	Date	Local time	U_6	U_1	$\bar{U}_6$	$\bar{U}_1$	$\bar{U}_{10}$	z_0	U_*
	1919	h m	m/s	m/s	m/s	m/s	m/s	cm	cm/s
2	Sep. 7	10 00	3.7	2.3	4.7	2.9	5.2	5.4	40
		12 00	4.3	2.1					
		14 00	6.2	4.4					
3	Sep. 7	16 00	3.8	1.8	4.9	2.6	5.6	13.0	51
		18 00	5.5	2.6					
		20 00	5.5	3.5					
1	Sep. 8	08 00	7.0	5.1	5.6	4.0	6.1	1.1	38
		10 00	4.3	3.0					
Mean					5.1	3.2	5.6	5.0	42

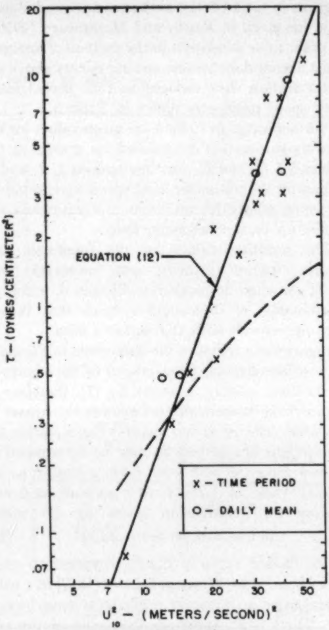

FIG. 6 – The surface stress plotted against the square of the ten-meter wind speed

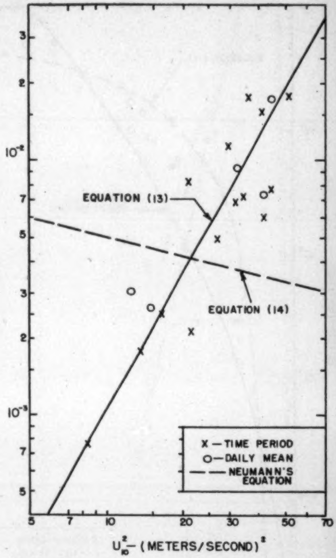

FIG. 7 – The resistance coefficient plotted against the square of the ten-meter wind speed

An interesting feature of Figure 7 (or (13)) is that it shows the resistance coefficient increasing almost twice as fast as the square of the ten-meter wind speed. This is very much in disagreement with the findings of other researchers (see *Hay* [1955b], *Neumann* [1956], or *Dietrich* and *Kalle* [1957] for a summary of the better known values). In particular, Neumann has derived the empirical relationship

$$\gamma^2 = 9 \times 10^{-3} \left(\frac{100 \text{ cm/sec}}{U} \right)^{1/2} \tag{14}$$

between the wind speed and the resistance coefficient based on the results of sea-surface slope observations.

Eq. (14) is plotted as a dashed line in Figure 7. The discrepancy between (13) and (14) is quite obvious. Unfortunately, wind profile corrections of the type suggested by *Neumann* [1951] will not cause any better agreement between these two formulas, since the net result of the corrections is to give an increase in the value of the computed resistance coefficient.

Even though the individual points in Figures 3–7 show some scatter, there is no indication of any discontinuity in the general trend of the points. This is in disagreement with *Munk's* [1947] hypothesis that a wind velocity of 7 m/s at 15 m was accompanied by a discontinuity in the resistance coefficient and initiated the occurrence of whitecaps. Neither of these discontinuities was evident in the present analysis. This is not the first time the critical wind-speed concept has been questioned [*Neumann*, 1956]. Even *Munk* [1957] has conceded that the existence of a critical wind speed is somewhat doubtful.

An attempt was made to relate the roughness parameter to the water-level fluctuations as measured by a step wave gage. Because the roughness parameter was found to increase with the ten-meter wind speed and because wind waves also increase in amplitude with increasing wind speeds, one would intuitively expect a relationship be-

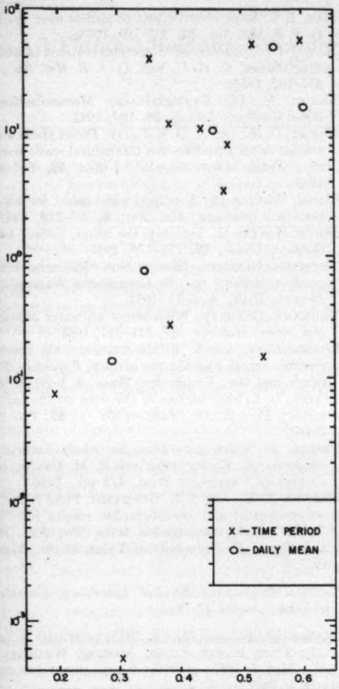

FIG. 8 – The roughness parameter plotted against the water-level fluctuation root-mean-square value

tween these two parameters. A plot of these data is shown in Figure 8. Although there is some indication of a relationship, the plotted points have considerable scatter. This scatter is thought to be caused by the inability of the wave gage to separate the wind effects on the water surface from the swell. For example, on April 19 the roughness parameter was found to be 0.15 cm while the root-mean-square of the water level fluctuations was computed to be 0.53 foot. Visual observations of the water surface during this time period show that the water-surface fluctuations were almost entirely caused by a smooth sea swell from the southeast with only occasional wind ripples. The problem of relating the roughness parameter to water level fluctuations, whether it be wind waves, ripples, or some other water surface disturbance, offers interesting possibilities for future research.

Data reliability—The anemometers used for these observations were calibrated in a wind tunnel less than two months before the start of the measurement program. After these calibration tests the anemometers were boxed and stored until mounted on the platform in the Gulf of Mexico. It is felt that sufficient calibration information was available to make errors from this source insignificant.

Many problems arose during the reduction of the data, only a few of which were resolved. The high starting torque of the anemometers made any mean wind speed below about five miles per hour (2.2 m/s) of doubtful reliability, therefore all profiles containing speeds below this figure were eliminated from the analysis. This does not mean that these lower wind speeds are unimportant as far as transfer processes at the air-water boundary are concerned. Instead we are simply stating that it was impossible to determine these low wind speeds with the accuracy necessary to arrive at valid conclusions, and for this reason they were omitted. Another problem was that of having only two usable anemometer levels. More levels would have been desirable in order to describe more accurately the over-water wind profile. In particular it would have been desirable to have at least one anemometer located closer to the water surface.

Even though a fixed oil drilling platform may have certain advantages over a raft as an observing station, certainly one of its disadvantages is the inability to keep the anemometers at a fixed height above the water surface. On a raft this problem is not completely solved, what with wind waves and swell to contend with, but the fixed platform presents the added complexity of tidal fluctuations. There may be some question as to the validity of employing a mean anemometer height correction, especially during periods of rapid tidal fluctuations, but it gives at least a first approximation as to the mean height of the anemometers above the water surface.

The final problem to be discussed is that of current. If the water is moving under the influence of wind, tide, or swell, then it seems probable that in order to make a true application of the wind profile equation, the wind speed should be measured relative to the speed of the surface water current. A somewhat analogous statement was made by *Ursell* [1956] when he said, "It may be necessary to measure wind velocities relative to the speed of travel of the roughnesses." Unfortunately, a current meter was not included in the instrumentation for this project. Also, since no investigator seems to be definite as to what these roughnesses represent over a water surface, it is indeed difficult to measure their speed of travel.

Conclusions—Open-air measurements of wind-speed profiles over water is indeed a complicated and intricate task. In general, the data and analyses reported in this paper tend to conflict with previous experimental findings. However, in most instances, some supporting data can be found. The only firm conclusion that can be reached is that which describes the apparent state of knowledge concerning the energy balance and transfer processes between the Earth's atmosphere and oceans; that is, we have much to learn. To insure at least partial success of future missions, the combined talents of the meteorologist and oceanographer are required, for only through cooperative efforts and well planned experiments can some of the present day problems be resolved.

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A Portable Raindrop Recorder for Semi-Continuous Determination of Size Distributions*

A. T. SPENCER AND D. C. BLANCHARD

Abstract—The recorder was designed to obtain adequate drop samples, in the size range of 50 to 2000 microns diameter, at about two-minute intervals for a period in excess of 24 hrs. Successful field use of several instruments in a cloud physics study is indicated and they are described in some detail.

Introduction—During the planning stages of Project Shower [*Blanchard* and *Spencer*, 1957; *Squires*, 1955] the need arose to obtain continuous records of the fluctuation of the raindrop size in the orographic clouds on the Island of Hawaii. This need grew out of earlier ideas [*Blanchard*, 1953; *Woodcock*, 1952] of the importance of detailed knowledge of raindrop size distributions as an aid to understanding 'warm' rain formation. The purpose of this paper is to describe the instrument which was designed to answer our questions about drop size and number differences as a function of time and substance within orographic clouds.

A variety of automatic sampling devices have been developed and used [*Bowen* and *Davidson*, 1951; *Cooper*, 1951; *Fugiwara*, 1954; *Katz*, 1952; *Maulard*, 1951], but none of them, with the possible exception of the raindrop spectrograph of Bowen and Davidson [1951], appeared to have sufficient accuracy, compactness, and portability for the present work. Thus it seemed advisable to design and build a small device that would incorporate the above features.

Earlier work in Hawaii had shown that the rain from orographic clouds was not uniform but that great fluctuation in intensity and rain drop size occurred. Individual showers, imbedded within the orographic cloud system, appeared to move up the mountain slopes while the median raindrop size progressively decreased with increasing elevation [*Blanchard*, 1953].

Since we needed to determine the rate of change of the drop distribution as a function of time and distance along the mountain slope, it was necessary to construct a number of portable instruments that could be used to obtain measurements simultaneously at several elevations. As no source of power was available on the mountain, the instruments had to be self-contained and portable. It was decided to build instruments that would expose a section of dye treated paper tape at intervals of about two minutes. The splash pattern on the tape could then be related to raindrop size by appropriate calibration methods.

Although the instrument to be described in this paper was designed specifically for use in Hawaiian orographic rains where the raindrops seldom exceed two millimeters diameter, there is no reason why minor changes in the design could not make it adaptable for use in heavier rains. The present design should also be adequate for the light steady rains that are commonly associated with the passage of a warm front.

Instrument description—The dimensions of the drop recorder shown in Figures 1-3, are 6 × 8 × 11 inches. It weighs twelve pounds, excluding the weight of the power source. The operation of the recorder is as follows: at two minute intervals a sliding shutter opens and exposes a section of paper tape to the rain. The shutter remains open for approximately 2.7 sec. During the nearly two-minute period that the shutter is closed, the paper tape is dried by a heating coil and the 'take up' spool advances an unexposed section of paper tape into position for the next exposure.

The tape is standard, 3½ inches wide, adding machine paper which was impregnated with dry methylene blue chloride powder. Sufficient dye was polished into the paper, as illustrated on Figure 4, to produce a uniform pale blue color.

The opening in the cover, through which the rain falls (see Fig. 2) has an area of only 33 cm². However, past studies of typical trade-wind shower rains [*Blanchard*, 1953] show that a two or three-second exposure allows from 60 to 200 drops to be collected on a 33 cm² surface. In most cases this is a sufficient number to establish the drop size distribution with useful accuracy.

The two small, 12-v dc motors and the 16-watt

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* Contribution number 979 from the Woods Hole Oceanographic Institution.

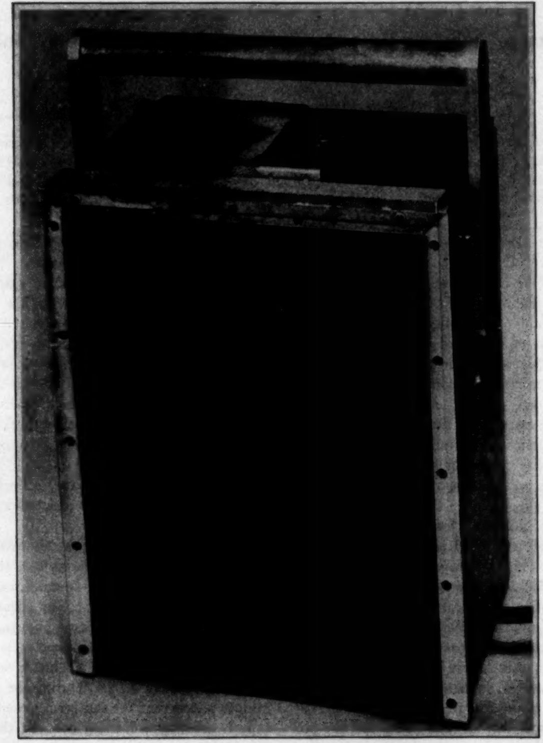


FIG. 1 – Front view of recorder showing ventilation louvers in access door and sliding door in closed position

heater coil of the recorder, are powered by a 12-v dc automobile battery. This battery will operate the recorder for 24 hrs without recharging. One of the two motors runs continuously as a timing motor. The second motor transports the paper and opens the sliding hatch to expose the tape. The heating coil is turned off, shortly before the tape is exposed, to prolong the life of the battery between charging periods.

The top surface of the case, as well as the sliding shutter, are made of Formica, a laminated plastic material of low heat conductivity. This allows the inside surface of the cover and hatch to attain a sufficiently high temperature so that condensation of the water vapor, which is evaporated from the tape does not take place. There is sufficient space between the sliding hatch or shutter, and the top surface for the vapor from the drying tape to escape to the outside air. Circulation is facilitated by the ventilation louvres revealed on Figure 1.

The fine wire mesh, which stands approximately ¼ inch above the top surface, prevents raindrops from striking the outside rigid surfaces and splashing onto the tape when the shutter is open. The splash of raindrops striking the wire mesh or the paper tape was negligible for drops of less than two

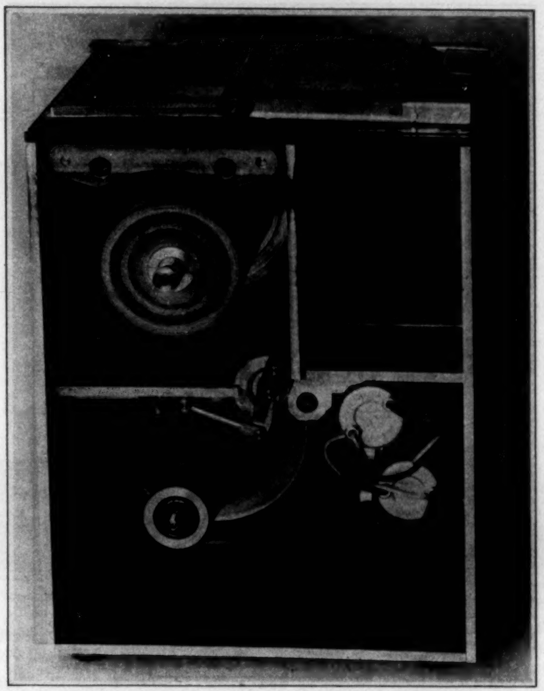


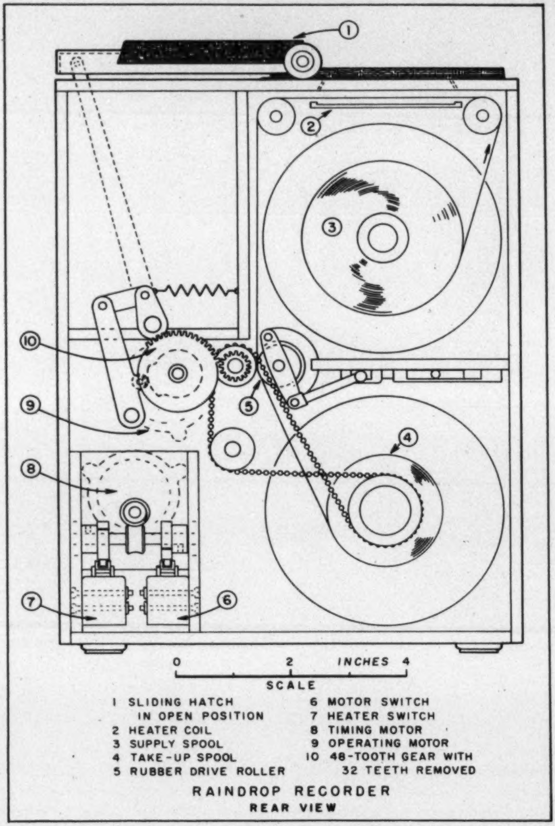
FIG. 2 – Front view of raindrop recorder with access door removed, and showing sliding door in open position

millimeters diameter. For drops larger than two millimeters the splashed drops were generally smaller than 0.2 mm.

The relatively constant rate of rotation of the small dc motors, produces a usefully constant relationship between the length of paper tape exposed and time. Thus the time of exposure of any given rain record can be extrapolated or interpolated from a few time marks manually placed on the tape during a 24-hr period.

Discussion—The drop recorders obtained excellent records in the Hawaiian orographic rains when the rain did not exceed intensities of about 25 mm hr^{-1} (see Fig. 5). The exposure time of 2.7 sec was satisfactory even when sampling the very light rains in the range of 0.1 to 1 mm hr^{-1}. Although the drops in these light rains are generally less than 500 microns diameter and thus have a low settling speed, they are present in great numbers. Consequently, the number of drops striking the recorder tape per unit time will often equal, if not exceed, that when the rain intensity is higher. This will hold true only when the sampling is done in a region where the small drops are not subject to evaporation in their fall from source to ground. At intensities greater than about 25 mm hr^{-1} the increased size of the imprint pattern of the drops resulted in overlapping and in the production of small drops by splashing.

The calibration of the recorder tape was done by letting various sized drops strike the tape at terminal velocity. Drops as small as 50 microns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SCALE
1 SLIDING HATCH IN OPEN POSITION
2 HEATER COIL
3 SUPPLY SPOOL
4 TAKE-UP SPOOL
5 RUBBER DRIVE ROLLER
6 MOTOR SWITCH
7 HEATER SWITCH
8 TIMING MOTOR
9 OPERATING MOTOR
10 48-TOOTH GEAR WITH 32 TEETH REMOVED
RAINDROP RECORDER
REAR VIEW

FIG. 3 – Sectional view of recorder with back removed; this view shows the mechanisms for transporting the paper tape and opening the sliding hatch; a cam and switch which stops the operating motor (see Fig. 3, no. 9) after 360° of rotation, is not shown here

diameter leave imprints on the dyed tape that are sharp and clear. With such small drops a low-power microscope is necessary to measure the imprint. The imprint diameter is a function of raindrop size and is from 1.5 times the drop diameter at 50 microns to about ten times the drop diameter at two millimeters. In the range commonly associated with raindrops ($>$ 200 micron diameter) the original drop size may be determined from the imprint diameter by using a properly calibrated scale. With the aid of graphs, the drop distribution thus obtained may be converted into rain intensity or the volume distribution of raindrops.

An instrument of the type here described is useful in many cloud physics and radar weather studies. Further discussion of the use of the re-

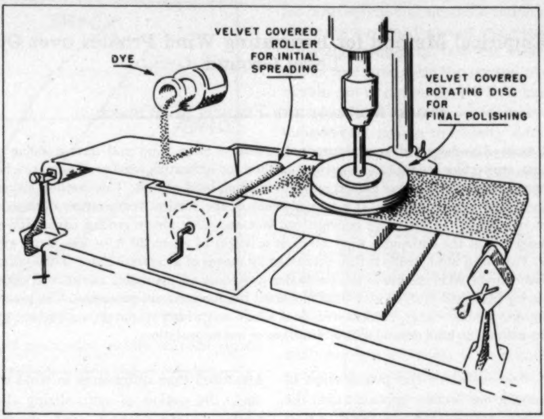
DYE
VELVET COVERED ROLLER FOR INITIAL SPREADING
VELVET COVERED ROTATING DISC FOR FINAL POLISHING

FIG. 4 – Method of impregnating paper

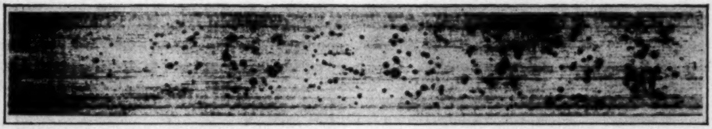

FIG. 5 – Portion of an exposed three-inch paper tape from the recorder, showing consecutive samples

corders in Hawaii are available [*Blanchard*, 1957; *Blanchard* and *Spencer*, 1957].

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An Empirical Method for Estimating Wind Profiles over Open, Level Ground

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Abstract—An analysis of several hundred measured mean wind and corresponding mean temperature profiles has led to an empirical method for estimating wind profiles up to a height of approximately 30 ft above ground cover over open, level ground. This method makes use of two simple measurements: (1) a measurement of the vertical temperature difference between two heights in the range between one foot and 15 ft above ground cover, and (2) a measurement of the horizontal wind speed at a height of about 30 ft or less above ground cover. The mean wind profile is then estimated by means of a contour chart. The limitations and errors involved in the use of this prediction procedure are discussed, and several examples comparing predicted profiles with their measured counterparts are presented. The procedure is proposed for the many practical situations where one wishes to obtain approximate wind profiles over open, level ground with a minimum of instrumentation.

Introduction—In studies of the propagation of sound over ground it has become apparent that the vertical wind and temperature gradients which exist between source and receiver profoundly affect the attenuation of the acoustic signal [*Ingard*, 1953; *Keast* and *Wiener*, 1957]. These gradients produce a gradient of the speed of sound with height which results in refraction of the sound rays. Thus, in order to predict the sound attenuation for a given set of conditions, the wind and temperature profiles over the sound path along the ground must be known. Wind profiles near the ground are of interest also in the study of atmospheric turbulence in the boundary layer, both theoretically [*Davidson* and *Lettau*, 1953] and in relation to the dispersal of atmospheric contaminants [*Cramer*, 1957].

Currently available analytical expressions for the vertical profiles of mean horizontal windspeed [*Sutton*, 1953] contain constants, such as the roughness length and friction velocity. These parameters must either be determined by direct experiment or estimated from tabulations compiled by a number of investigators in this field. Direct measurement of the wind profile requires accurately calibrated and rather costly instrumentation.

The present technique of estimating the wind profile for the first 30 ft above open, level ground is proposed for the many practical situations where one wishes to obtain approximate vertical profiles of mean wind speed with a minimum of instrumentation and computation. Utilizing measurements of a vertical temperature difference between some intermediate heights and of the wind speed near the top of the range of heights of interest, this technique makes use of the fact that temperature differences are usually more easily and accurately measured than differences in wind speed. In addition, the notion of normalizing the mean wind profile to the highest wind speed measured is introduced.

Based on an analysis of several hundred wind and corresponding temperature profiles measured simultaneously over open, level ground, the proposed method is discussed in the following Sections and its limitations are pointed out. Several examples are presented showing a comparison of predicted and measured profiles. Developed for use in estimating outdoor sound attenuation over open, level ground, it is hoped that this technique is of use in other fields as well.

The shapes of mean temperature and wind profiles—The dependence of the general shape of the wind profile near the ground on the thermal stratification is well known. Figure 1 shows idealized profiles of the mean wind speed plotted against height on a logarithmic scale. The profile is generally concave upward for unstable conditions (stability ratio $SR \equiv \Delta T/\bar{u}^2 < 0$), but concave downward for stable conditions ($SR > 0$). For neutral stability conditions ($\Delta T = S = 0$) the profile is very nearly logarithmic. This has been confirmed by numerous investigators, notably *Best* [1935], *Thornthwaite* and *Kaser* [1943], and others.

Idealized temperature profiles near the ground are shown in Figure 2 plotted against height on a logarithmic scale. There is general agreement in the literature [*Sutton*, 1953; *Best*, 1935; *Deacon*, 1949] that the temperature profile is logarithmic for neutral and near-neutral conditions. Concerning the shape of the temperature profile for other conditions of convective stability there is less

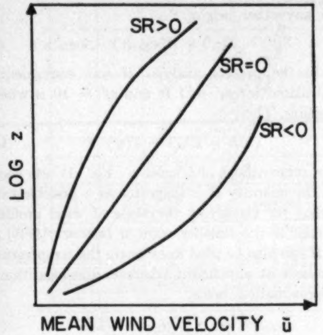

FIG. 1 - Idealized mean wind profiles near the ground

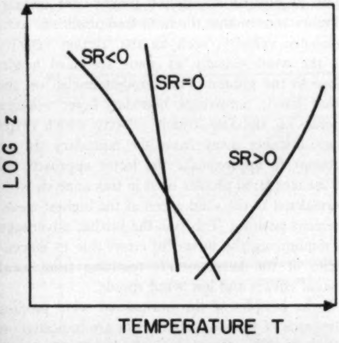

FIG. 2 - Idealized temperature profiles near the ground

agreement. *Lettau* and *Davidson* [1957, appendix to v. 1] has concluded from an analysis of data taken at O'Neill, Nebraska, "that the logarithmic profile form exists in the surface layer only as a transient state, when the thermal stratification passes through neutral." But ***Halstead*** [1954] has analyzed the curvatures of wind and temperature profiles of some of the O'Neill data through heights up to about 20 ft and concluded that both temperature and wind profiles do not depart too far from a logarithmic relation with height except at times of great thermal stability. Examination of the large body of experimental data referred to in this paper which includes all of the O'Neill data tabulated [*Lettau* and *Davidson*, 1957, v. 2] shows that the temperature profile can be approximated by a logarithmic relation in a large number of cases, for both stable and unstable conditions, the cases of strong thermal inversion excepted.

On the assumption that the mean temperature profile measured near the ground over open, level terrain can be approximated by a logarithmic relation, one can use the logarithmic slope of the temperature profile to classify and estimate the corresponding wind profiles near the ground. The method proposed here uses this slope in conjunction with the measured wind speed at a suitable height to estimate the corresponding mean wind profile with the aid of a generalized contour chart. The results obtained show that this is a workable procedure resulting in useful engineering estimates of the wind profiles in many cases.

Measurements of wind and temperature profiles—The following four sets of profile data have been analyzed in the course of developing the profile prediction procedure, providing a total of about 600 pairs of wind and temperature profiles.

(1) Johns Hopkins University measurements [*Lettau* and *Davidson*, 1957; *Johns Hopkins University*, 1953] at O'Neill, Nebraska, from July 29, 1953, to September 8, 1953, consisting of about 300 wind profiles (hourly averages) measured over open, level ground, with corresponding temperature profiles. The ground cover was mowed grass about 0.17 ft high.

(2) Massachusetts Institute of Technology measurements [*Lettau* and *Davidson*, 1957] at O'Neill, Nebraska, from August 4, 1953, to September 8, 1953, consisting of about 200 wind profiles (hourly averages) with corresponding temperature profiles.

(3) Massachusetts Institute of Technology measurements (private communication) at Round Hill, South Dartmouth, Massachusetts, from December 1, 1954, to November 8, 1955, consisting of about 25 wind profiles measured over open, level ground with corresponding temperature profiles. The ground cover was grass about 0.5 ft high.

(4) *Bolt*, *Beranek*, and *Newman*, *Inc.* [1957] measurements in conjunction with sound propagation studies at Deblois, Maine, between September 23 and October 12, 1955, consisting of about 30 wind profiles measured over open, level ground with corresponding temperature profiles measured. The ground cover was grass and low bushes about a foot high.

In addition to the above four sets of data, a set not included in the analysis was used to check the empirical prediction procedure: Texas A & M measurements (private communication) at O'Neill, Nebraska, from July 3 to August 30, 1956, consisting of about 65 wind profiles measured over open, level ground with corresponding temperature profiles.

Analysis of the temperature profiles—Eight sample daytime and nighttime profiles chosen at random from each of the four sets of data are plotted in Figure 3. The ordinate is a logarithmic scale of height z' above ground cover. (The height of the ground cover is defined as the mean elevation of the tops of the vegetation above ground.) This is a simplification made throughout the analysis in order to eliminate the differences in the mean heights of the ground covers at the various measurement locations.

A study of Figure 3 indicates that most of the temperature profiles are roughly logarithmic, at least between one and 10 to 15 ft above ground cover. This has been found to be particularly true when the gradient is negative, as is usually the case during the daytime and, of course, for near-neutral conditions. Two additional profiles are shown which deviate markedly from the logarithmic relation. They illustrate the variability of the profile shapes found especially at night during stable conditions.

If one approximates the temperature profile by a straight line plotted against the logarithm of the height above ground cover, one can define the profile by a constant slope H. Thus, for a given temperature difference at heights z_1' and z_2'

$$H = \frac{T(z_2') - T(z_1')}{\log_{10}(z_2') - \log_{10}(z_1')} \text{ °F} \qquad (1)$$

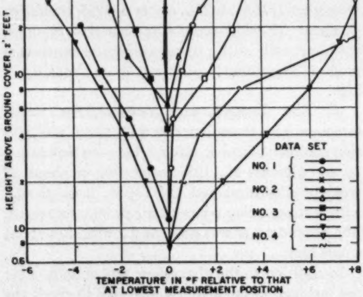

FIG. 3 – Selected measured mean temperature profiles from each of the four data sets

At any other height, z'

$$T(z') - T(z_1') = H[\log_{10}(z') - \log_{10}(z_1')] \qquad (2)$$

In the present analysis H was conveniently calculated for $z_1' = 1$ ft and $z_2' = 10$ ft where possible. Then

$$H = T(z_2') - T(z_1') \text{ °F} \qquad (1a)$$

For other values of z_1' and z_2', Eq. (1) was used.

The quantity H is suggested as a possible candidate for classifying the slope of wind profiles, similar to the stability ratio or *Deacon's* [1949] β.

H can also be used to estimate the temperature gradient at any height wherever the logarithmic approximation holds.

$$\partial T/\partial z = \partial T/\partial z' = H/2.3z' \qquad (3)$$

Analysis of the wind profiles—In the analysis of wind profiles, it is common practice for meteorologists to normalize the measured profiles to some reference velocity, such as the friction velocity or the wind velocity at some standard height close to the ground. The aerodynamicist, on the other hand, normalizes boundary-layer velocity profiles to the free-stream velocity which exists some distance away from the boundary. In an attempt to approximate the latter approach, all of the measured profiles used in this analysis were normalized to the wind speed at the highest measurement position. This has the further advantage of minimizing the spread of errors due to inaccuracies of the anemometers resulting from local ground effects and low wind speeds.

Eight samples of the normalized wind profiles from each of the four sets of data are indicated on Figure 4. (These profiles are not necessarily companion profiles of the temperature profiles shown in Fig. 3.) These profiles are plotted against height above ground cover. In addition, each profile is labeled with the value of H determined from two points on its corresponding temperature profile. The samples on Figure 4 have been chosen to provide a wide range in H, and it is evident from the figure that a correspondingly wide range of profile shapes has resulted. Comparison of Figure 4 with Figures 1 and 2 suggests the possibility of using H, like SR or β, as a parameter associated with the shape of the profile.

The possibility of a correlation between wind profile shape and H is brought out somewhat more clearly in Figure 5. Here, all the profiles plotted on Figure 4 are normalized to the wind speed at the same height, in this case 30 ft above ground cover. (When actual measurements were not

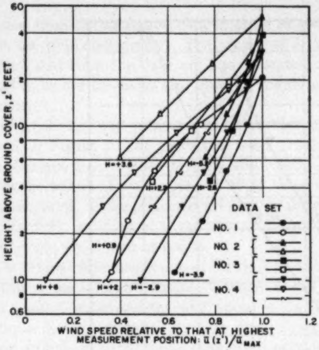

FIG. 4 – Selected measured mean wind profiles from each of the four data sets; the abscissa is normalized to the wind speed at the highest measurement position

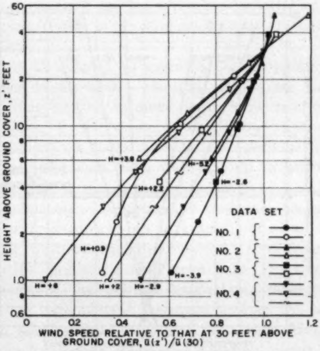

FIG. 5 – Mean wind profiles replotted against wind speed normalized to the wind speed at 30 ft

obtained at 30 ft, the wind speed at this height was interpolated or extrapolated, as required, from the data at the other measurement points.) It is clear from Figure 5 that the steeper profiles which are concave upward are associated with negative values of *H*, and the profiles which are concave downward accompany positive values of *H*. In addition, there is an indication that a relationship exists between the shape of the profile and the magnitude of *H*, as well as its sign, although some exceptions to this are evident.

The results of the analysis of all 600 profile pairs analyzed in the manner outlined above are condensed in the generalized profile prediction contours shown in Figure 6. (Notes on its derivation are given in the Appendix.)

One enters the graph with a known value of *H*, either determined from a known temperature profile, or obtained from a measurement of the temperature difference between two points, in the range between 1 ft and 15 ft above ground cover. The corresponding normalized wind profile is then read from the ordinate scale at the intersections of a vertical line placed at *H* on the abscissa and the families of curves shown for z' = 1 ft, 2 ft, 4 ft, etc., above ground cover. The actual estimated wind profile is then obtained by multiplying the values of normalized wind speed by the mean wind speed at 30 ft, which is obtained by direct measurement. If the wind speed is measured at some other height less than 30 ft, the normalized profile is used to calculate the wind speed that would have been measured at a height of 30 ft and that value is used to obtain the actual estimated profile. If desired, the wind gradient may then be estimated from the profile at any point, most conveniently perhaps by graphic means.

An indication of the accuracy of the proposed method is provided by examining the spread of the data points through which the contours of Figure 6 were drawn as averages. This spread is indicated by the cross-hatched areas and applies to about 80 per cent of the measured points. For $H > +4$ very little data exist, although occasional values of *H* as large as 12 or 15 were encountered. In this region the curves in Figure 6 are shown dashed.

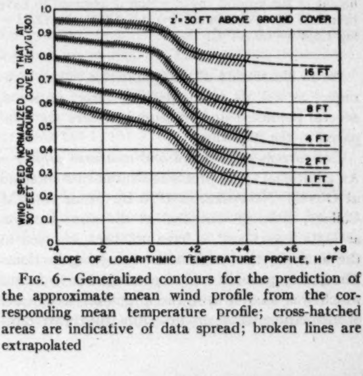

FIG. 6 – Generalized contours for the prediction of the approximate mean wind profile from the corresponding mean temperature profile; cross-hatched areas are indicative of data spread; broken lines are extrapolated

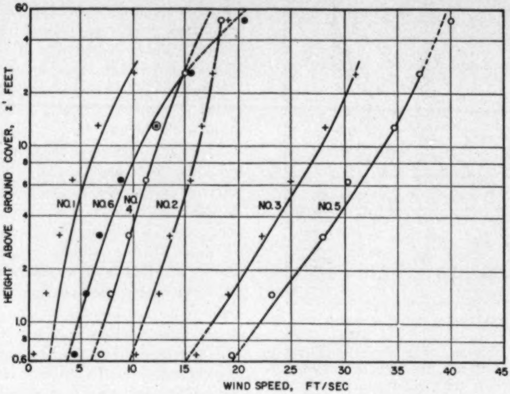

FIG. 7 – Comparison of predicted and measured profiles of mean wind speed; the points indicate measured values

TABLE 1 – *Six test examples*

Example	Date	Time		Measured ΔT between 0.5m + 4m[a]	Calc. value of H	Measured wind speed at 30 ft (interpolated)
	1956	h	m	°C	°F	ft/sec
1	July 6	01	05	+2.55	+4.8	10.2
2	July 11	12	05	−2.53	−4.8	17.7
3	July 14	08	08	−1.28	−2.4	31.2
4	July 23	20	05	+0.44	+0.8	15.2
5	Aug. 7	15	05	−1.77	−3.4	37.5
6	Aug. 25	22	35	+1.49	+2.8	16.0

[a] All quantities measured in metric units were converted to English units. Thus: 0.5m = 1.63 ft; 4m = 13.1 ft; ΔT°F = 9/5 ΔT°C. Subtracting the mean height of the ground cover, which is assumed to have been 0.17 ft, we obtain H °F = 9/5 ΔT°C/(log 12.93 − log 1.46) = 1.9 ΔT°C.

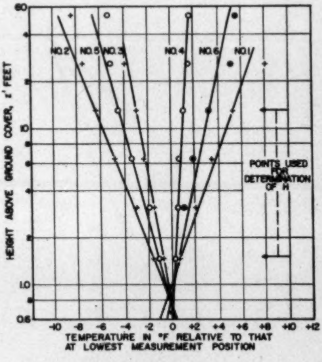

FIG. 8 – Comparison of logarithmic temperature profile relation and observed points

As an illustration of the application of this technique, as well as of the possible errors involved, several predicted and measured profiles are compared in the following.

Comparison of predicted and measured profiles—An additional set of profile measurements obtained at O'Neill, Nebraska, in 1956 by Texas A & M College, although obtained at the same location as Data Sets 1 and 2, have not been included in the analysis discussed in the foregoing Sections. Thus, they provide an independent body of data which was used to test the proposed techniques of estimating wind profiles from measured temperature differences between two points and the measured wind speed at a third.

Six examples have been chosen at random from these data to provide a wide range of wind speed and temperature conditions. For each of these examples, the measured temperature difference between the 4m and the 0.5m measurement heights has been used to calculate H. In addition, the value of the wind speed at 30 ft was interpolated from the measured data. Table 1 lists the information obtained from the measured data in order to construct the predicted profiles. The values of H in °F calculated from the data are also indicated in the table, as are the dates and times of the measurements.

The predicted and measured wind profiles are plotted in Figure 7. The predicted wind profiles were obtained from Figure 6, using the values of H and the values of wind speed at 30 ft listed in the above table. These predicted profiles are shown as solid lines on Figure 7, the actual measured wind speeds are shown as points.

It is evident from inspection of Figure 7 that the greatest errors arise in Example 1, where H has a large positive value and the wind speed is low. In Example 3, the predicted profiles also indicate higher values of wind speed than were actually measured, although the errors are smaller. For the rest of the examples, the deviation between the measured points and the predicted profiles is ten percent or less. Note that the gross curvatures of the measured profiles which are important for the computation of the wind gradient are predicted correctly.

It is of interest to examine the temperature profiles in the above examples and to see how well they fit the assumed logarithmic relation. In Figure 8, the assumed logarithmic relations (solid lines) are compared with the experimentally determined points. It is seen that up to heights of about 15 ft the agreement is fair.

Conclusions—The procedure described permits one to approximate, up to a height of about 30 ft, the mean wind profiles over open, level ground with low, uniform ground cover from (1) a measurement of the vertical temperature difference between two points in the range between 1 ft and 15 ft above ground cover, and (2) a measurement of the mean wind speed at a height of about 30 ft or less.

In carrying out this procedure, the assumption has been made that the temperature profile can be approximated by a logarithmic function. Its logarithmic slope is used to estimate and classify the corresponding mean wind profile. Experimental evidence indicates that this is reasonable in many cases, especially for unstable and near-neutral temperature stratification when errors in estimating the wind profile appear tolerable for many applications. For stable conditions, however, the temperature profile may depart appreciably from the logarithmic relations; also, the errors in estimating the wind profile are large under those conditions.

If desired, estimates of the wind gradients near the ground can be obtained from the estimated wind profile. The logarithmic temperature profile approximation yields estimates of the temperature gradient as a function of height. These gradients have been found useful for the estimation of the attenuation of sound propagated along the ground. Perhaps the estimated wind profiles and the gradients obtained therefrom are also adequate for other applications, where the micrometeorological instrumentation necessary for the direct measurement of wind profiles is too expensive or cannot be used for one reason or another.

Acknowledgments—All profile data analyzed in the course of this study, Data Set 4 excepted, were kindly provided prior to their publication by H. E. Cramer of the Round Hill Field Station of the Massachusetts Institute of Technology, South Dartmouth, Massachusetts. This assistance, and the help and encouragement extended the authors by him and his staff throughout this study are gratefully acknowledged. This work was supported by the U. S. Signal Corps under Contract DA-36-039 SC-64503 with Bolt, Beranek, and Newman, Inc.

APPENDIX

The detailed procedure followed in the preparation of Figure 6 is as follows: Values of H were obtained from the temperature profiles corresponding to each wind profile. For this purpose, temperature readings at the following heights were used: (a) 40 cm and 320 cm for Data Set 1; (b) 2m and 4m for Data Set 2; (c) 1.5m and 3m for Data Set 3; and (d) 0.75 ft and 8 ft for Data Set 4.

Then, for each wind profile, the wind speeds at the various heights were normalized to that at the greatest height where measurements were obtained (as in Fig. 4). The resulting normalized profiles were then plotted as points on a sheet similar to Figure 6, except that the ordinate was different in each case, namely, (a) $V(z')/V(21\text{ ft})$ for Data Set 1; (b) $V(z')/V(52\text{ ft})$ for Data Set 2; (c) $V(z')/V(38\text{ ft})$ for Data Set 3 and (d) $V(z')/V(30\text{ ft})$ for Data Set 4.

Similarly, the height parameters z' were different in each case because the measurement heights differed. An average curve for each measurement height was then drawn through the points on these figures, resulting in four sets of curves similar to those in Figure 6. Average profiles for different values of H could then be constructed from these average curves. From these average profiles, it was possible to interpolate normalized wind speeds at the same heights for all the sets of data and to renormalize these to the interpolated value of the wind speed at $z' = 30$ ft. Figure 6 was constructed from these interpolated, renormalized values.

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Characteristics of Waves Generated by a Local Disturbance

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Abstract—Waves generated by an initial local elevation or depression of uniform height were investigated in a two-dimensional model. The height of the elevation or depression, the extent of the disturbed area, and the water depth were varied. The model data were compared with the theories of *Unoki* and *Nakano* [1953] and *Kranzer* and *Keller* [1955]. It was found that within certain limits of water depth, height, and extent of disturbed area the wave characteristics, such as phase periods and interference pattern, could be described reasonably well. The magnitude of the wave heights was not predicted satisfactorily.

Introduction—The purpose of the investigation was to determine if the characteristics of waves caused by a local disturbance of the water surface could be formulated reliably by theory. The practical value of this is found in its application in the prediction of the wave motion resulting from an underwater seismic disturbance or a near-surface or underwater explosion. A literature survey is given by *Prins* [1956], in which three groups of solutions are considered: (1) initial elevation or depression of the surface without initial velocity, (2) undisturbed surface with an initial distribution of a surface impulse, and (3) undisturbed surface with an initial distribution of a submerged impulse (underwater explosion).

Owing to the practical limitations of the model study the following reported investigations were restricted to group (1), considering only the two-dimensional case of an elevation or depression of uniform height.

Experimental equipment and procedure—The model investigations were carried out in a flume one foot wide by 60 ft long. At one end of the channel it was possible to create a free elevated or depressed area with all the water particles effectively at rest. At the opposite end of the channel a wave absorber was installed. The vertical movement of the water was recorded simultaneously at five places along the channel ($\eta - t$ curves). The model set-up is given in Figure 1. The extent L and the height Q of the elevations or depressions and the water depth h were varied by steps: $h = 2.3$, 0.5, 0.35, and 0.2 ft; $L = \frac{1}{3}$, 1, and 2 ft; $Q = \pm 0.1$, ± 0.2, and ± 0.3 ft.

MATHEMATICAL DESCRIPTION OF THE PHENOMENA

The formulation of the problem in regard to the model investigation was to describe the water-surface position with respect to the undisturbed water level as a function of place and time when a disturbance consisting of an elevation or depression with a constant height Q extended over a length L in a two-dimensional system of water depth h was released. In general

$$\eta = f(Q, L, h, x, t) \tag{1}$$

The two following cases given in the literature are applicable to the given conditions.

Unoki-Nakano equation—The two-dimensional case of an initial elevation of a finite area in water of infinite depth has been formulated by ***Unoki*** and *Nakano* [1953] as follows: initial conditions at $t = 0$: velocity potential, $\phi_0 = 0$; elevation, $\eta_0 = Q$ at $-L < x < L$, and $\eta_0 = 0$ at $|x| > L$.

Solution

$$\eta = \frac{4Q\,x^{\frac{1}{2}}}{\pi^{\frac{1}{2}} g^{\frac{1}{2}}\, t} \sin\left(\frac{gt^2}{4x} \cdot \frac{L}{x}\right) \cdot \cos\left(\frac{gt^2}{4x} - \frac{\pi}{4}\right) \tag{2}$$

for $x \gg L$.

Wave characteristics: the phase period is defined by $\cos(gt^2/4x - \pi/4)$ so that

$$T = \frac{4\pi x}{gt}, \lambda = \frac{8\pi x^2}{gt^2}, C = \frac{2x}{t}\left(= \sqrt{2\pi}\right) \tag{3}$$

The amplitude variation of the waves is defined by $\sin\,(gt^2/4x)\cdot(L/x)$, with the qualities

$$T_1 = \frac{4\pi x}{gt} \cdot \frac{x}{L}, \lambda_1 = \frac{8\pi x^2}{gt^2} \cdot \frac{x}{2L},$$

$$C_1 = \frac{x}{t}\left(= \frac{1}{2}\sqrt{\frac{g\lambda}{2\pi}}\right) \tag{4}$$

Kranzer-Keller equation—The three-dimensional case of an initial elevation or depression of a finite area in water of finite depth has been formulated by *Kranzer* and *Keller* [1955] as follows: initial conditions at $t = 0$: shape of elevation, $E(r)$; elevation at the origin, ζ_0; effective radius of displacement, R.

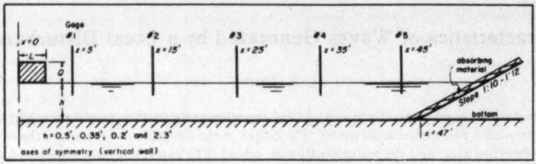

FIG. 1 – Model set-up

Solution

$$\zeta_e = \zeta(r, t) \approx \frac{\zeta_0 R}{r} \mathrm{B} \cos 2\pi \left(\frac{t}{T} - \frac{r}{\lambda}\right) \quad (6)$$

for $r \gg R$ and $B = 0$ at $r > \sqrt{gh} \cdot t$, in which R is defined by

$$\tfrac{1}{2} |\zeta_0| R^2 = \int_0^\infty |E(r)|\, r\, dr \text{ and}$$

$$\pi |\zeta_0| R^2 = \text{displaced volume} \quad (7)$$

Wave characteristics: the linear theory of surface waves is applied and the functions are expressed in terms of the auxiliary variable $\sigma = 2\pi h/\lambda$, which is defined as the unique non-negative root of the equation

$$\phi(\sigma) = \tfrac{1}{2} \sqrt{\frac{\tanh \sigma}{\sigma}} + \frac{1}{2 (\cosh \sigma)^{3/2}} \sqrt{\frac{\sigma}{\sinh \sigma}} = \frac{r}{\sqrt{gh} \cdot t} \quad (8)$$

The phase period is defined by $\cos 2\pi (t/T - r/\lambda)$, so that

$$T = \frac{2\pi}{\sqrt{\frac{g\sigma}{h}} \tanh \sigma}, \quad \lambda = \frac{2\pi h}{\sigma},$$

$$C = \sqrt{\frac{g\lambda}{2\pi} \tanh \frac{2\pi h}{\lambda}} \quad (9)$$

The amplitude variation of the waves is defined by the B-term, which is expressed as follows

$$B = \frac{1}{\zeta_0 R h} \bar{E}\left(\frac{\sigma}{h}\right) \sqrt{\frac{\sigma \phi(\sigma)}{-\phi'(\sigma)}} \text{ at } r < \sqrt{gh} \cdot t \quad (10)$$

in which $\bar{E}(\sigma/h)$ is the zero-order Hankel transformation of the initial elevation $E(r)$ and is given by

$$\bar{E}\left(\frac{\sigma}{h}\right) = \int_0^\infty E(r) J_0 \left(\frac{\sigma r}{h}\right) r dr \quad (11)$$

For water of finite depth σ/h becomes $gt^2/4r^2$ and the equation turns into

$$\zeta_e = \zeta(r, t) \approx \frac{\zeta_0 R}{r} B \cos \frac{gt^2}{4r} \quad (12)$$

with wave characteristics

$$T = \frac{4\pi r}{gt}, \quad \lambda = \frac{8\pi r^2}{gt^2}, \quad C = \frac{2r}{t} \sqrt{\frac{g\lambda}{2\pi}} \quad (13)$$

$$B = \frac{\sqrt{2}}{\zeta_0 R} \cdot \frac{gt^2}{4r^2} \cdot \bar{E}\left(\frac{gt^2}{4r^2}\right) \quad (14)$$

COMPARISON OF EXPERIMENTAL RESULTS AND THEORY

The experimental data are given as $\eta - t$ curves at a fixed place from which the required quantities can be deduced, such as phase period, phase zero points, amplitude envelope zero points and wave amplitudes.

The equation given by *Unoki* and *Nakano* [1953] is directly applicable to the investigated case for infinite water depth. As the waves are dispersive there will be a region where the water is deep enough to be considered as infinite with respect to the waves ($h/\lambda > 0.5$).

The equation of *Kranzer* and *Keller* [1955] deals with the three-dimensional case. The two terms determining the oscillating system can be applied as well to the two-dimensional case. However, the wave amplitudes can not be calculated. For the shape of the disturbance $E(r)$ the elevation of constant height has to be introduced.

Special attention has to be given to the leading part of the generated wave train. The characteristics of the leading disturbance are dependent on the ratios Q/h and L/h, as is shown schematically in Figure 2.

The following types of the leading part could be distinguished: (1) leading wave with oscillatory characteristics, being part of the dispersive wave pattern (O), (2) leading wave with solitary wave

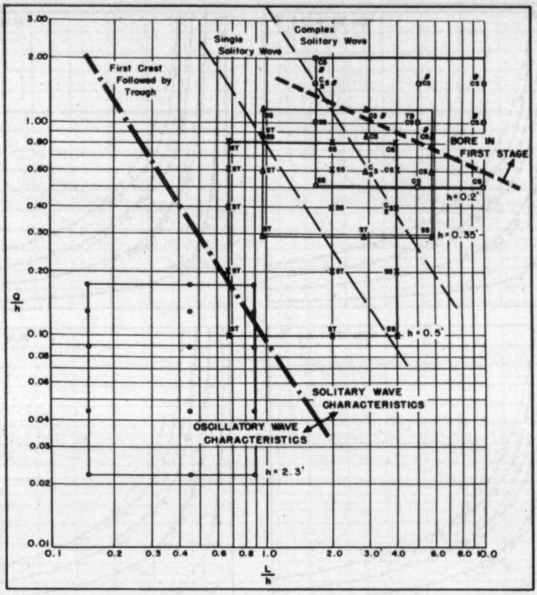

FIG. 2 – Relation between *L/h*, *Q/h* and the characteristics of the leading wave in the case of elevation

characteristics with respect to its velocity of propagation, followed by a trough connecting it with the dispersive wave pattern (ST), (3) leading wave being a single wave with solitary wave characteristics, separated from the dispersive wave pattern by a more or less flat part at the still-water-level (SS), and (4) leading part being of complex form, which, while traveling outward, breaks up into a few waves with solitary wave characteristics separated from the dispersive wave pattern (CS).

For certain conditions either a bore (B) or a top bore (TB) occurred which did not seem to affect appreciably the type of leading wave.

The following is restricted to the case for which the leading disturbance has the characteristics of an oscillatory wave. The other types have been discussed extensively by *Prins* [1958].

Phase period—In the $t - T$ plane the theoretical curves for the $t - T$ relation at constant x can be plotted according to (3) at infinite depth, and to (9) at depth h.

The curve for finite depth starts to deviate from the infinite depth curve at $h/\lambda = 1.0$ and at large periods approaches $\sqrt{gh}$. The evaluation of this curve can be made by using (8) for σ as a function of $x/\sqrt{gh}\cdot t$.

Eq. (8) also may be written as $x = C_{gr}\cdot t$ (15) in which

$$C_{gr} = \tfrac{1}{2}\left[1 + \frac{\dfrac{4\pi h}{\lambda}}{\sinh\dfrac{4\pi h}{\lambda}}\right]\left(\tanh\frac{2\pi h}{\lambda}\right)\cdot C_0$$

$$\text{and } C_0 = \frac{g}{2\pi}\cdot T$$

The ratio C_{gr}/C_0 as a function of h/λ_0 is tabulated by *Wiegel* [1954].

The formula $x = C_{gr}t$ shows that a wave reach-

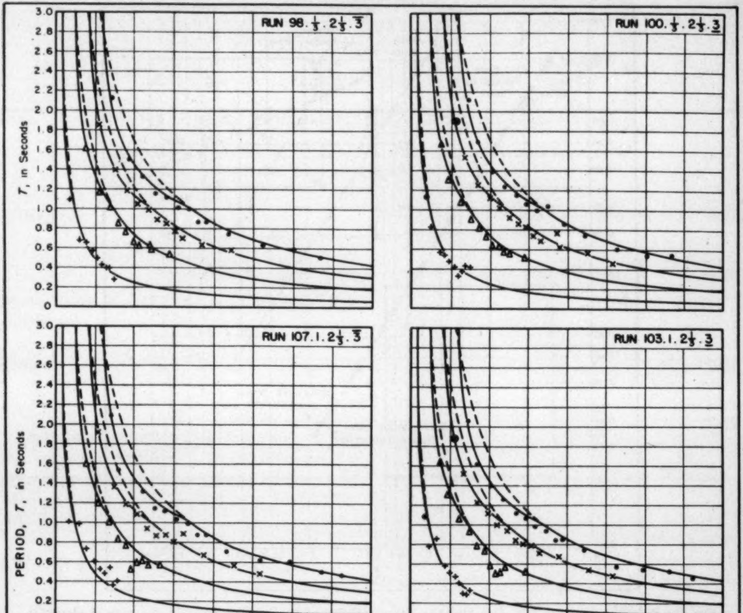

FIG. 3 – t-T relationship for water depth $h = 2.3'$, dashed line $T = 4\pi x/gt$ (infinite depth theory), solid lines Kranzer and Keller theory for $h = 2.3'$

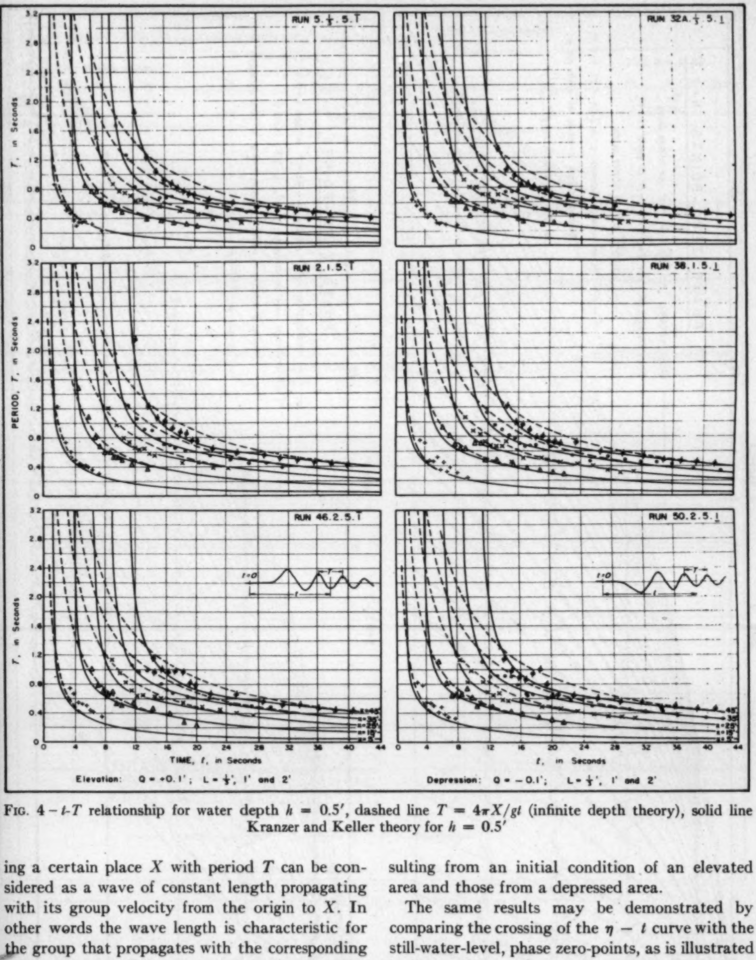

FIG. 4 – t-T relationship for water depth $h = 0.5'$, dashed line $T = 4\pi X/gt$ (infinite depth theory), solid line Kranzer and Keller theory for $h = 0.5'$

ing a certain place X with period T can be considered as a wave of constant length propagating with its group velocity from the origin to X. In other words the wave length is characteristic for the group that propagates with the corresponding group velocity. This was noted by *Lamb* [1956, art. 238–241 and 255] for water of infinite depth.

Figures 3 and 4 show the agreement of the experimental values with the theory. It proves that the deviations increase with increasing L. There is no essential difference between the waves resulting from an initial condition of an elevated area and those from a depressed area.

The same results may be demonstrated by comparing the crossing of the $\eta - t$ curve with the still-water-level, phase zero-points, as is illustrated in Figure 5.

The amplitude envelope curve—The relatively long periodic phenomenon defining the amplitude variation can be determined by considering the location of the zero points. It has also a dispersive character.

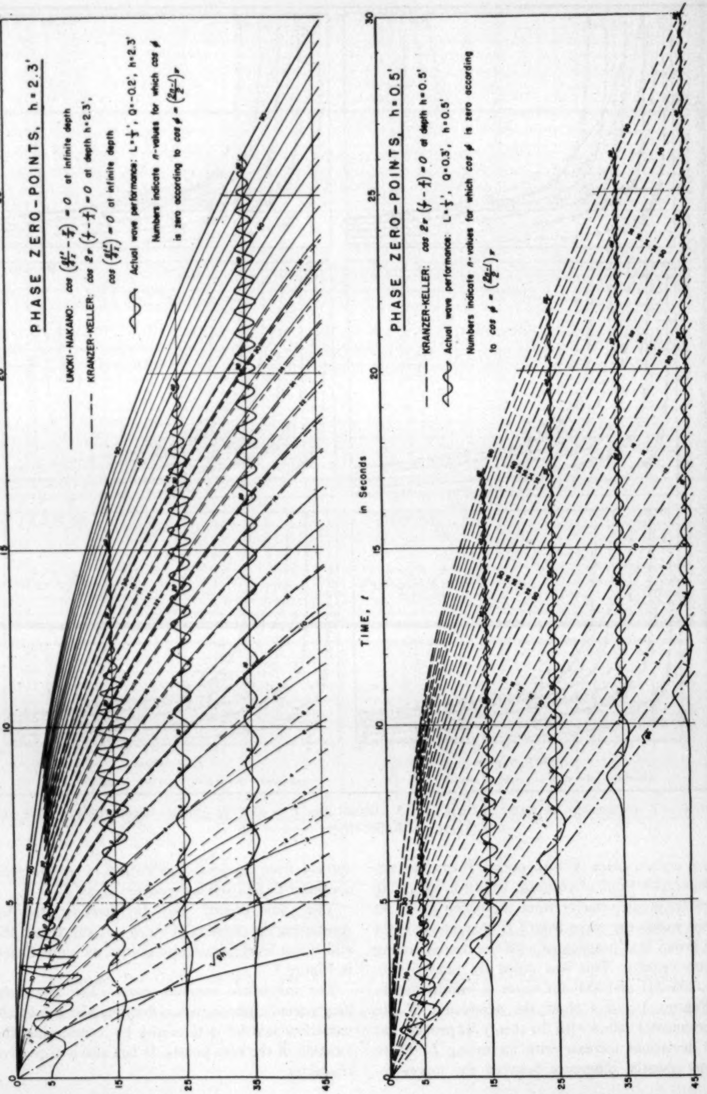

FIG. 5 – Phase zero-points, h = 2.3' and 0.5'

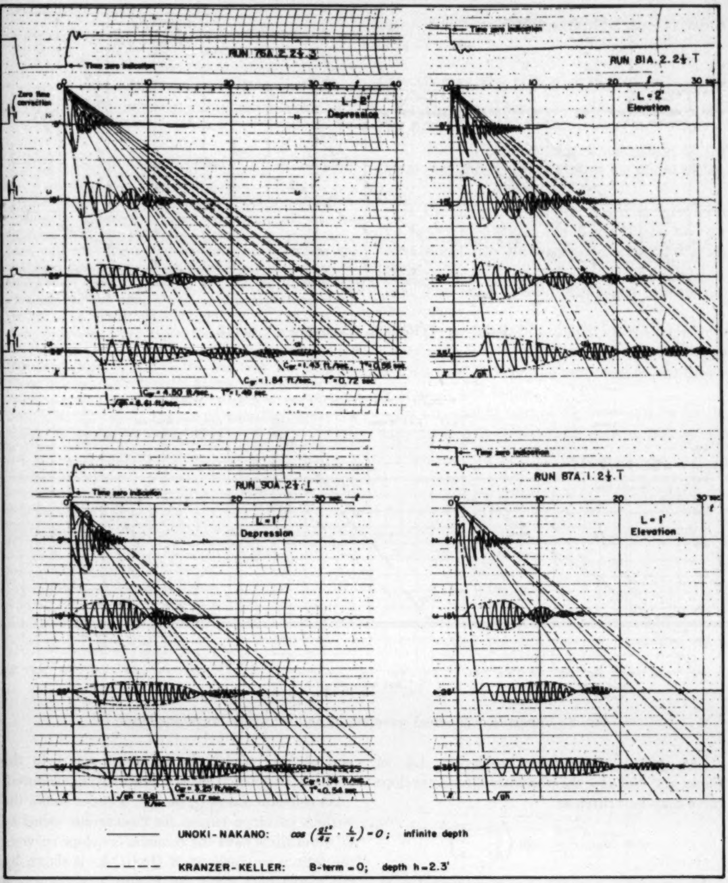

FIG. 6 – Amplitude envelope zero-points, $h = 2.3'$

The location of the envelope zero point is given by Unoki and Nakano as sin $(gt^2/4\ x\cdot L/x) = 0$, or $x/t = \sqrt{L}\ \sqrt{g/4n\pi}$ at $n = 0, 1, 2, \cdots$. In the $x - t$ plane the velocity of propagation of the zero points should be constant and proportional to $\sqrt{L}$.

According to Kranzer and Keller the envelope zero points will occur when $B = 0$. By introducing the initial conditions of the model, this will happen when the Bessel function of the first order $J_1[(\sigma/h)L] = 0$. At $\sigma > 3$ the position of the zero points proves to be independent of the water depth and the velocity of propagation (x/t) proportional to $\sqrt{L}$.

The experiments show a good agreement with the condition of Unoki and Nakano as is illustrated by Figure 6, especially at the larger extents of the disturbed area.

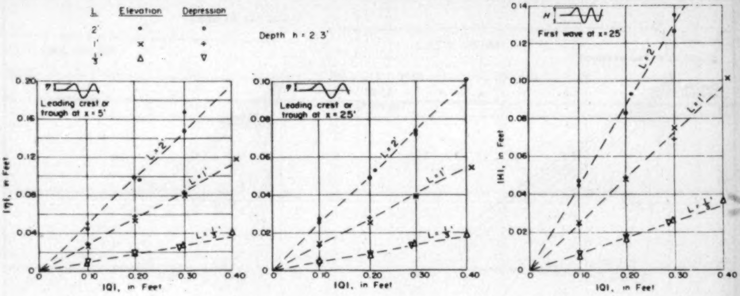

FIG. 7 – η—Q Relation at constant x, t, and L

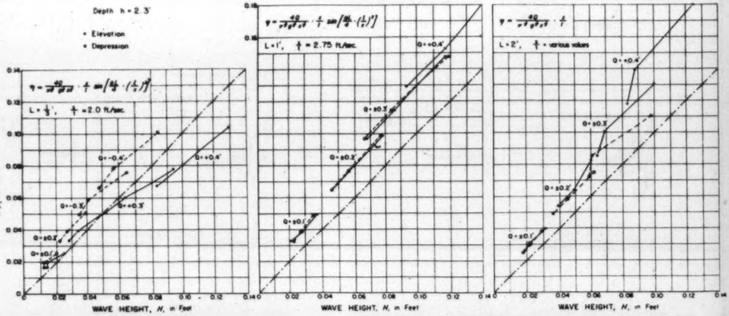

FIG. 8 – Comparison of actual wave height and calculated wave amplitude

The phase amplitudes—Considering (2) of Unoki and Nakano, the phase amplitude envelope curve may be written as

$$\eta = \text{const.}\,\frac{Qx^{\frac{1}{2}}}{t}\cdot\sin\left(\frac{gt^2}{4x}\cdot\frac{L}{x}\right)$$

At constant x, t, and L, η is proportional to Q. In regard to the leading crest or trough it was found that η was directly proportional to Q. There was no difference between the case of an initial elevation or depression. Figure 7 presents some model data, and Figure 8 presents the relationship of actual wave heights to calculated amplitude.

At constant x/t (elimination of the sine term), L, and Q, η is proportional to $x^{-\frac{1}{2}}$. At depth h = 2.3 ft the results shown in Table 1 were obtained for the ratios of the amplitudes η_{15}/η_{25}, η_{15}/η_{35}, and η_{25}/η_{35}, where the subscript refers to the position X at which the amplitudes were measured.

At constant x and Q, the $\eta - t$ curve shows the various envelope curves for the various values of L. All of these have the common envelope curve of the form η = constant $\times\, Q\, x^{\frac{1}{2}}/t$. As is shown by the model data given by Figure 9, there was a definite tendency for a common envelope curve to exist for different values of L. In considering the energy distribution within the wave pattern, together with the area of disturbance, it was found that when the disturbance was extended vertically, the character of the wave pattern was maintained with the amplitudes being proportional to the vertical change of disturbance. When the disturbance was extended horizontally, the wave pattern changed its appearance, but the amplitudes did not exceed those of the common envelope

TABLE 1

L	Theoretical ratio		
	η_{15}/η_{25} 1.29	η_{15}/η_{35} 1.52	η_{25}/η_{35} 1.18
ft			
2	1.53[a]	1.76	1.16
1	1.35	1.69	1.24
$\frac{1}{3}$	1.39	1.60	1.15

[a] Average from values at $Q = +0.4$ through $Q = -0.4$. The agreement was not satisfactory. It was not expected that the theoretical amplitudes would compare well with the actual measurements, because the envelope amplitude in the theoretical case was different from the actual values (see Fig. 6). By properly choosing the x/t value it was possible to obtain better results. The actual wave heights H at constant x/t were compared with twice the amplitude calculated by the use of (2). This has been shown in Figure 8 (for the plot for $L = 2$ ft, the sine term was assumed to be unity). Again there is little or no difference between the data for an initial condition of elevation or an initial depression. The actual values of H did not reach the theoretical values of 2η.

curve, which was independent of the variation of L.

CONCLUSIONS FOR $Q/h < 0.18$ AND $L/h < 0.9$

(1) The generated wave pattern was of a dispersive character.

(2) The variation of height and extent of the initial disturbance did not affect the phase velocities.

(3) The phase periods were found to agree with the theory of *Kranzer* and *Keller* [1955], and for 'deep water' with the theory of *Unoki* and *Nakano* [1953].

(4) The wave pattern showed an interference phenomenon.

(5) The position of the amplitude envelope zero-points was found to be well expressed by the theory of Unoki and Nakano and fairly well by the theory of Kranzer and Keller.

(6) The leading part of the wave pattern for the case of an initial elevation showed exactly the

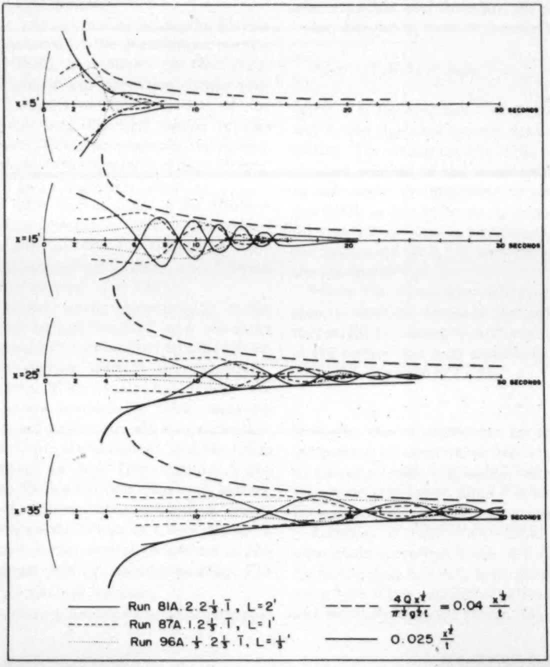

FIG. 9 – Amplitude envelope curves with constant Q and variations of L

negative performance of the waves generated by an initial depression ($\eta_{elev} = -\eta_{depr}$).

(7) The amplitudes of the leading waves were found to be directly proportional to the height of the initial disturbance.

(8) The wave amplitudes did not show a satisfactory agreement with the theoretical values according to Unoki and Nakano. In general the measured values were found to be smaller than the theoretical values.

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An Interpretation of the Transverse Component of the Geomagnetic Electrokinetograph Readings in the Florida Straits off Miami

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Abstract—The transverse component of the Florida Current was studied by the Geomagnetic Electrokinetograph (GEK), the use of which is reviewed for the Florida Current. Based on 422 GEK fixes taken over a five-year period, including three special time series, two constituent surface transverse components are shown to exist, both of which involve a return flow at greater depths. One constituent resembles the downstream advection of an internal wave with its current reversing sign every 8 to 16 hours. The other is a diverging surface flow in the free stream apparently explainable in terms of the vorticity equation.

Introduction—*Pillsbury* [1880] studied the transverse motion in the Florida Current by relating the current width to the Moon's declination. *Parr* [1937] described his study of transverse component in terms of 'transverse extrusion.' Careful navigators of the current are also aware of transverse motion; many charts, for example, U.S.C.& G.S. chart 1112, show current arrows at an angle to the longitudinal direction.

Consecutive velocity profiles across the Florida Current, as measured by the geomagnetic electrokinetograph (GEK), have shown complex variations in longitudinal and transverse components. This paper attempts an interpretation of the transverse component. The first section reviews the validity of GEK measurements in the Straits. The second considers the reduction of data. Presentation of data and a discussion follow.

Validity of GEK measurements in the Straits—The use and interpretation of GEK measurements have been treated by *von Arx* [1950] and more generally by *Longuet-Higgins*, *Stern*, and *Stommel* [1954, hereafter referred to as LSS].

Let the essential electric characteristics of the Florida Current be approximated by a two-layer system contained in a non-conducting channel: an upper, faster, uniform current over a slower, uniform current. When their thicknesses are separately uniform horizontally, GEK measurements in the x and y directions will bear a constant ratio to those of the actual current, and the GEK current directions are real. This condition is not realized in the Florida Current. However, barring windage effect, any consistent pattern of transverse GEK component involving a sign change is real, fluctuation in the vertical component of the Earth's magnetic field H_z notwithstanding. For simplicity, H_z is assumed constant.

To see this clearly, consider the GEK potential in the y direction as given by LSS

$$E_y = \frac{\partial\varphi}{\partial x} S_x + \frac{\partial\varphi}{\partial y} S_y + V_x H_z S_y - V_y H_z S_x \qquad (1)$$

(always for zero cable droop and vertical motion), where S_x, S_y and V_x, V_y are distances between towed electrodes, and speeds relative to the Earth along the x and y directions, respectively; and where the first two terms are the potential in the water. For the S_y term, it is given by

$$\frac{\partial\varphi}{\partial y} S_y = -V_x H_z S_y - \rho i_y S_y \qquad (2)$$

where ρ is the electrical resistivity of the water and i_y the electrical current density in the y direction. The strong current shear observed in the Current consists of the term $(\partial v_y/\partial x)$ and thus cannot affect the alignment of electrodes towed due north or south; hence S_x is zero in (1). That (2) may not be zero in the Straits merely affects the magnitude of E_y; it does not effect an E_y in the absence of V_x.

Where the (vertically) averaged current $\overline{V}$ is high, a direction change in the surface GEK current might be caused by a change in the speed V of the surface skin layer relative to $\overline{V}$ as given by LSS in their equation 2.2.13

$$\rho i_x = (V - \overline{V}) H_z \qquad (3)$$

However, this is improbable for the longitudinal component as observation has always shown V to exceed $\overline{V}$; and it is highly improbable for the transverse component since $\overline{V}$ is always near zero because of the return flow at greater depth.

Reduction of GEK data—GEK measurements were made according to *von Arx* [1950] following his sailing plan A-2 with fixes about 40 min apart using both Navy demolition cables (balsa buoyed) and neutrally buoyant cables. Measurements are therefore subject to windage but free from cable droop. To correct for windage, the method of *Knauss* and *Reid* [1957, hereafter referred to as KR] is used. Since the conditions KR assumed do not all apply to the Florida Current, it is desirable to restate the windage problem for the Florida Current.

The base course of the research vessel is usually south of east or west to offset the current drift; hence the ship's track over bottom is generally due east or west. The potential measured when heading east is, in KR notation

$$E_x = \frac{\partial\varphi}{\partial x} S_x + \frac{\partial\varphi}{\partial y} S_y' - V_y H_z S_x + V_x{}^* H_z S_y' + V_x H_z S_y' \quad (4)$$

On the two fix courses, the measured potentials are

$$E_y = \frac{\partial\varphi}{\partial x} S_x' + \frac{\partial\varphi}{\partial y} S_y - V_y{}^* H_z S_x' + V_x H_z S_y - V_y H_z S_x' \quad (5)$$

$$E_{-y} = \frac{\partial\varphi}{\partial x} S_x' - \frac{\partial\varphi}{\partial y} S_y + V_y{}^* H_z S_x' - V_x H_z S_y - V_y H_z S_x' \quad (6)$$

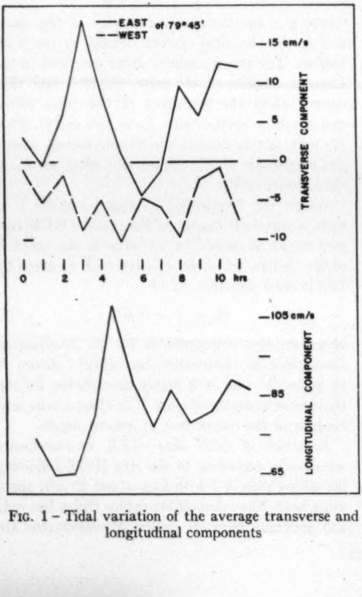

FIG. 1 – Tidal variation of the average transverse and longitudinal components

TABLE 1 – *Average GEK current components*

Solar hr[a] after high water at Miami Beach	North component	East component	No. of observations
	cm/s	cm/s	
East of longitude 79°45′			
0	63.2	3.1	16
1	39.7	−0.5	11
2	41.3	6.1	11
3	64.3	18.2	13
4	101.8	9.2	11
5	75.8	1.1	10
6	54.6	−4.4	16
7	65.4	−1.0	16
8	70.1	9.7	22
9	77.6	5.9	14
10	75.1	12.6	17
11	77.3	12.1	14
			171
West of longitude 79°45′			
0	79.4	−1.1	35
1	79.9	−5.2	18
2	78.0	−1.7	21
3	89.3	−8.7	17
4	112.1	−4.9	20
5	92.7	−10.2	27
6	94.2	−4.7	21
7	106.5	−5.8	17
8	88.6	−9.6	18
9	83.5	−2.3	18
10	102.6	−0.8	18
11	93.7	−7.6	21
			251

[a] The hour zero includes the interval from 0–59.9 minutes plus the interval in excess of 12 hr.

where the primed letters represent those components of the vector separation of the electrodes that are perpendicular to the ship's course, and the asterisked letters, the speed of the vessel relative to water. Following *von Arx* [1950], the zero point is

$$\tfrac{1}{2}(E_y + E_{-y}) = \frac{\partial\varphi}{\partial x} S_x' - V_y H_z S_x' \quad (7)$$

The potential $\bar{E}_x$, the value used in computing V_y in (8), is

$$\bar{E}_x = E_x - \tfrac{1}{2}(E_y + E_{-y}) \quad (8a)$$

Or

$$\bar{E}_x = \frac{\partial\varphi}{\partial x}(S_x - S_x') - V_y H_z (S_x - S_x') + V_x{}^* H_z S_y' \quad (8)$$

after dropping the small terms involving S_y'. The potential $\overline{E}_y$, the value used in computing V_x in (5), is obtained by the subtraction of (7) from E_y,

TABLE 2 – *First group*[a] *of GEK data averaged as to positions and east-west components*

GEK measurements	Positions[b]								
	1	2	3	4	5	6	7	8	9
With west components									
Average magnitude, cm/s	17	17	22	16	18	18	18	14	11
Number of observations	55	22	10	9	9	8	9	11	16
North magnitude, cm/s	62	103	99	164	109	90	60	49	37
With east components									
Average magnitude, cm/s	14	20	19	23	24	23	16	17	12
Number of observations	16	15	19	16	17	15	15	13	19
North magnitude, cm/s	52	93	120	128	109	84	75	34	29
With zero east-west component	2	5	1	1	2	2	1	0	1

[a] Data collected during December 1952–June 1956 and are used here uncorrected, see text.

[b] Position 1, west of Longitude 80° W to Miami Sea Buoy; Position 2, 79°55′–79°59.99′; Position 3, 50′–54.99′; Position 4, 45′–49.99′; Positions 5, 6, 7, 8, every 5′ interval as above; Position 9, east of 79°24.99′ to Great Bahama Bank.

TABLE 3 – *Second group*[a] *GEK data averaged as to positions and east-west component*[b]

GEK measurements	Position[c]								
	1	2	3	4	5	6	7	8	9
With west component									
Average magnitude, cm/s	28	5	6	7	15	12	9	6	12
Number of observations	6	2	17	10	1	2	2	1	3
Average north magnitude	110	118	89	115	151	86	46	81	33
With east component									
Average magnitude, cm/s	21	26	13	13	27	24	14	10	18
Number of observations	2	1	12	22	3	5	5	4	6
Average north magnitude	87	85	102	129	103	85	82	60	50

[a] This group consists of the corrected data listed in Tables 5 and 6.

[b] Five measurements had zero east-west components; these are not tabulated.

[c] See Table 2, footnote b.

or

$$\overline{E}_y = \frac{\partial\varphi}{\partial y} S_y - V_y{}^* H_z S_x' + V_x H_z S_y \qquad (9)$$

Solving (8) and (9) for V_y and V_x respectively, one has

$$V_y = -\overline{E}_x/(S_x - S_x')H_z + (1/H_z)\frac{\partial\varphi}{\partial x} + V_x{}^* S_y'/(S_x - S_x') \quad (10)$$

and

$$V_x = \overline{E}_y/(H_z S_y) - (1/H_z)\frac{\partial\varphi}{\partial y} + V_y{}^* S_x'(1/S_y) \qquad (11)$$

The two second terms in (10) and (11) are independent of windage and electrode spacing and are dependent solely on the environment; they can be considered constants and be absorbed in their respective first terms as far as windage is concerned. Eq. (10) differs from KR's in another aspect: $(S_x - S_x')$ instead of S_x in the denominator. Usually, S_x' is less than 0.1 S_x. KR indicated that the ratio of S_y' to S_x is 0.05 for 50 pct cable immersion, a vessel speed of 9 knots and wind of 12 m/s. For 7-knot speed of our vessel and for the same wind speed and immersion, the ratio is 0.07. The last term in (10) is thus $(0.075)V^*$ compared

TABLE 4 – *The prevailing winds during cruises of the first group*

Cruise	Date	Prevailing winds	Number of GEK fixes	
			A	B
	1952			
T240	Dec. 22–23	N, NW, NE		12
	1953			
T311	Feb. 17	N		11
T312	Feb. 24	SSE	11	
T313	Feb. 27	W, SW	6	
T315a, b	Mar. 12–13	S	16	
T316	Mar. 17	NNW		7
T320a, b	Mar. 26–27	N		13
T323a, b	Apr. 28–29	N		15
T325	May 12	ENE		4
T331	May 26	ESE, SE		9
T339a, b	June 25–26	SSE	16	
T347	July 23	SE		3
T349a, b	Aug. 4–5	E, S	8	8
T352a, b	Aug. 24–25	SSE	15	
T353	Sep. 22	SE		6
T355	Oct. 2	E		11
T358a, b	Oct. 23–24	N, NNW		14
T362	Nov. 10–11	N		6
T364a, b	Nov. 24–25	S, W	14	
	1954			
T402	Jan. 21	ESE		8
P430	July 16	S	15	
	1955			
G5501	July 13–15	ESE		15
G5509	Sep. 27–28	ENE, E		17
G5520	Nov. 29	N		9
G5524	Dec. 21	N		8
	1956			
G5607	Feb. 14	E, ESE		14
G5614	June 25	Calm, S	18	
			119	190

to $0.05V^*$ in KR. However V^*, the speed of the vessel relative to water, in this study is 78 pct of that in KR; hence the magnitudes of these terms are within 9 pct of each other. More fundamentally,

TABLE 5 – *East component of Cruise G5618, September 1956*

Transect	Date	Time		Wind Direction	Wind Speed	GEK current I[a]	GEK current II[b]
		h	m	°	m/s	cm/s	cm/s
A Miami–Cat Cay	24	11	52	180	4	0	8
					4	−1	4
					4	3	7
					6	6	14
					6	−15	−7
					6	−12	−5
					6	5	13
					6	−6	1
					6	13	22
		18	25		6	18	26
C Miami–Cat Cay	25	19	15	200	4	22	30
					4	26	33
					4	41	49
					4	31	40
					3	49	55
					3	41	47
					4	10	18
					5	11	22
	26	01	15	250	7	4	22
D Cat Cay–Miami		06	15	250	7	4	19
					7	9	25
					6	20	30
					6	22	36
					4	22	32
					4	21	30
					4	8	6
					4	−4	4
					4	20	26
		13	00		4	33	−24
E Miami–Cat Cay		18	15	270	4	−21	−14
						−8	0
						0	7
						−6	1
						9	17
						20	29
						7	14
						5	12
						11	19
	27	00	53			11	18
F Cat Cay–Miami		07	00	050	4	9	−2
					4	16	5
					4	27	15
					4	28	17
					5	11	−2
					7	12	−5
					9	6	−16
					8	−10	−31
		12	50		8	−1	−20

[a] Corrected east component.

[b] Uncorrected east component.

TABLE 6 – *East component of Cruises G5706 and G5707*[a]

Cruise	Sta.	Time		Wind Direction	Wind Speed	GEK current Corr.	GEK current Uncorr.
		h	m	°	m/s	cm/s	cm/s
G5706	A	14	00	100	2.5	−19	−24
	B	15	10			5	0
	A	16	20			−4	−8
	B	17	30			−13	−17
	A	18	38			−10	−14
	B	19	54			−6	−8
	A	21	00			−12	−17
	B	22	10			0	−5
	A	23	18			−6	−11
	B	00	27			6	2
	A	01	37			20	16
	B	02	43			7	4
	A	03	54			10	6
	B	05	00			14	11
	A	06	15			22	19
	B	07	25			16	13
	A	08	40			6	3
	B	09	50			2	−2
	A	11	05			−11	−15
	B	12	12			−15	−18
	A	13	24	100	3.5	−29	−36
	B	14	28			−2	−8
	A	15	38			−3	−9
	B	16	45			−9	−15
	A	17	55			3	−3
	B	19	03			12	7
From Sta. B to Cat Cay		20	15			16	10
		21	25			−23	−29
		22	35			−15	−21
		22	58			−11	−17
Cat Cay to Miami		08	50	180	5.0	−17	−10
		10	00			−1	−8
		11	09			−10	−5
		12	16			−14	−7
		13	08			−19	−12
		14	10			−51	−45
		14	31			−49	−42
G5707	A	11	44	057	4.0	−4	−14
	B	12	52		4.0	11	2
	A	13	55		5.0	−12	−24
	B	15	04		5.0	−9	−19
	A	16	07		5.0	−41	−53
	B	17	23		5.0	−28	−41
	A	18	25		5.0	−28	−40
	B	19	40		5.0	−23	−37
	A	20	43		6.0	−22	−38
	B	21	59		6.0	−9	−26
	A	23	00		7.0	−13	−33
	B	00	17		7.0	2	−17
	A	01	31		9.0	−2	−27
	B	02	47		9.0	5	−19
	A	03	54		9.0	0	−24
	B	05	13		10.0	−8	−33
	A	06	20		11.0	−13	−43
	B	07	34		11.0	17	−10
	A	08	41		11.0	−8	−36

TABLE 6 – *continued*

Cruise	Sta.	Time		Wind		GEK current	
				Direction	Speed	Corr.	Uncorr.
		h	m	°	m/s	cm/s	cm/s
	B	10	00		11.0	14	−15
	A	11	10		11.0	18	−10
	B	12	36		11.0	20	−9
	A	13	47		11.0	−2	−31
	B	15	20		13.0	13	−20
	A	16	33		13.0	11	−23

[a] Cruise dates: G5706: April 29 to May 1, 1957; G5707: May 6–7, 1957.

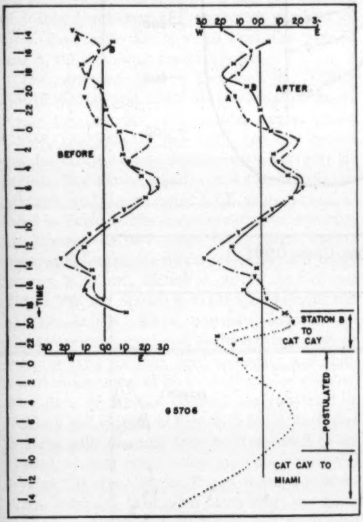

FIG. 2 – Observed and corrected transverse component, Cruise G5706

in addition to the question of wind measurement, there is considerable uncertainty regarding the effect of the sea state on both the drag coefficients and on the immersion of the cable. Thus, one is justified in using the values of KR windage correction.

The direction of the spurious component V_s caused by windage shall be downwind and its magnitude shall be

$$V_s \text{ (cm/s)} = 0.7\, W \text{ (m/s)} \qquad (12)$$

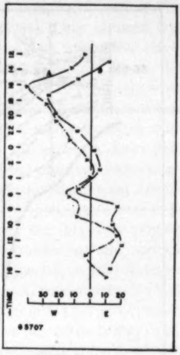

FIG. 3 – Corrected transverse component, Cruise G5707

where the factor 0.7 is the average of the two sets of KR data and W is the wind speed.

Local surface wind drift is subtracted from GEK measurements, in many instances, to study variations that are independent of local winds. As an approximation, the wind drift is taken as two per cent of the wind strength and directed at 45° to the right of the downwind direction. No allowance is attempted for coastal effect nor for complication from changing local winds [*Bowden*, 1953]. The adopted drift correction is often three times that for windage.

The wind drift correction is crude. This could be critical as in Cruise G5707 when winds exceeded 10 m/s on the second day. On calmer days, as in Cruise G5706, and when applied to a longer series, this is fortunately not significant.

The data—All GEK measurements made between latitudes 25° 30′ and 25° 57.9′N during the period December 22, 1952, to May 7, 1957, are used; 422 measurements are thus available.

To explore the relation of GEK data to direct tidal effect, uncorrected data are used in two groups with longitude 79° 45′W as the dividing line. Table 1 and Figure 1 summarize the arithmetically averaged north and east components according to observation hour with respect to Miami Beach predicted high water.

To avoid possible bias introduced by corrections, the basic data are regrouped on a time basis; one group is used corrected while the other is used uncorrected. They are arithmetically averaged

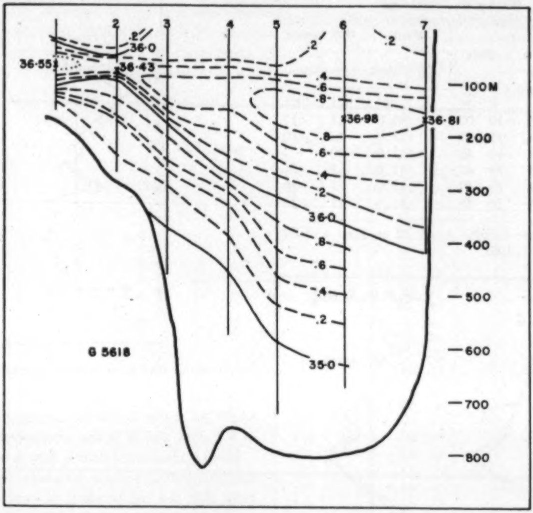

FIG. 4 – Salinity section, Cruise G5618

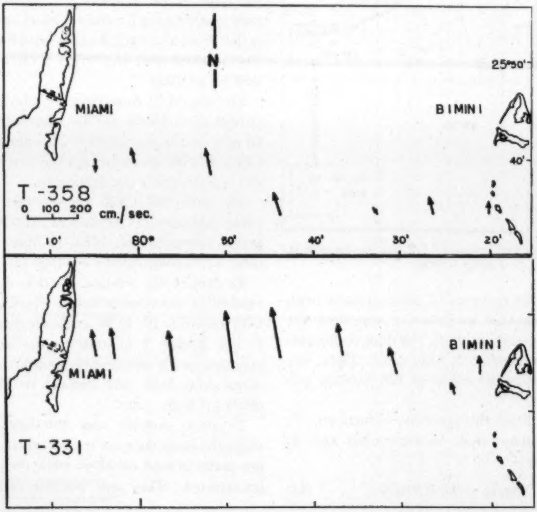
N
MIAMI
BIMINI
25°50'
40'
T-358
0 100 200
cm./sec.
10'
80°
50'
40'
30'
20'
MIAMI
BIMINI
T-331

FIG. 5 – Corrected GEK profiles of Cruises T331 and T358b, May 5 and October 24, 1953, respectively

with respect to their geographic locations and the results are listed in Tables 2 and 3 for data collected before and after June 1956 respectively. To assure that the result of Table 2 is not caused by local winds but may reflect the behavior of the Florida Current, local winds at cruise time are tabulated in Table 4. The winds are composites of shipboard observation, synoptic weather reports and winds at the tide stations at Miami Beach and Cat Cay. Considering the windage and wind drift corrections, one may label all winds clockwise from northwest to southeast inclusive (referred to as direction B) as having negligible part in effecting an eastward component. The last two columns of Table 4 tabulate the respective numbers of GEK fixes made during winds from directions B and A, the remaining compass points.

The corrected data of Cruises T331, T358b, G5618, G5706, and G5707 are intended to demonstrate the existence of horizontal waves. Cruise G5618, consisting of five GEK and one hydrographic transects, was executed with short rest intervals. The hours, dates, traverse direction of each transect, and the corrected GEK values are tabulated in Table 5. The continuity of data is assured by Cruises G5706-7 when GEK measurements were made consecutively for 28 hours each cruise at two locations: Station A at 25° 44.7′N and 79° 52.5′W and Station B at the same latitude but at 79° 45.9′W. These positions straddle the climatological current axis. Position determinations were by land sighting, dead reckoning, and shipboard radar and may be ½ mi off in poor weather. The data of Cruises G5706-7 are tabulated in Table 6 and plotted in Figures 2 and 3; in Figure 2, right half, the data have been extended by inclusion of data taken when the vessel proceeded to Cat Cay from Station B and during her subsequent return to Miami ten hours later; the words 'before' and 'after' mean before and after wind drift and windage corrections. The salinity section of G5618 and GEK transects of T331 and T358b are plotted respectively in Figures 4 and 5.

Discussion—GEK measurement of 'permanent' current is thought to be unaffected by tidal stream as the latter is considered constant with depth except in the friction layer. However, *Hela* and *Wagner* [1954] detected tidal influence, supported by present data in Figure 1, in the north component of GEK current. Since the resistivity of the channel bed is high and the width of the tide wave is narrow, it appears that the friction layer is relatively thick, a conclusion at variance with that of *Reid* [1958]. The question of tidal effect on the transverse component was studied by *Chew* and *Wagner* [1954]. They assumed that the semidiurnal tide is a long progressive wave and found that for a tidal amplitude of 40 cm, the transverse tidal stream exceeds 10 cm/s only when the depth is less than 160 m. This value is considerably less than many GEK values in deeper water.

One would also expect a direct phase relationship between the observed transverse component and the transverse tidal stream induced by shelving shores, if the tidal stream were to have a direct influence. Since the tide wave propagates southward, counterclockwise and clockwise rotary currents are expected in the western and eastern half of the Strait, respectively. No such pattern is apparent in Figure 1. This result implies that whatever transverse tide currents may exist are masked by stronger transverse currents whose origin is not directly tidal.

The higher frequency of eastward component over the westward one is shown clearly in Table 2, based on uncorrected data. That the result is independent of local winds is demonstrated in Table 4: 190 GEK fixes made when the winds would have favored a westward component compared to 119 fixes when the winds would have favored an eastward current. The same higher frequency feature is shown in Table 3 based on corrected data.

East of 79.9° W, greater frequency and greater magnitude of eastward component coincide, implying a net eastward surface transport. Similarly, a net westward surface transport is indicated west of 79.9°. In turn, convergences at both the western and eastern walls of the Strait are suggested. These aperiodic motions appear to be consistent with the vorticity equation.

Under reasonable restrictions and the assumption that $\partial v/\partial y = 0$, the change of the vertical component of absolute vorticity of a water parcel is

$$\frac{D}{Dt}(f + \zeta) = -(f + \zeta)\frac{\partial u}{\partial x} + \frac{\partial F}{\partial x} \qquad (13)$$

where $(f + \zeta)$ is the absolute vorticity, always positive. F is the boundary friction of the walls of the Strait, and $\partial u/\partial x$ is the east-west component of horizontal divergence. Near the western wall, $(\partial F/\partial x)$ is positive, $(\partial u/\partial x)$ is negative; hence the parcel gains absolute vorticity with time and so tends to increase its relative cyclonic shear. Near the eastern wall, both $(\partial F/\partial x)$ and $(\partial u/\partial x)$ are negative, hence the parcel tends to conserve its absolute vorticity. Away from the walls, $(\partial F/\partial x)$ in negligible, while mass continuity requires a positive $(\partial u/\partial x)$, hence parcels in the free stream tend

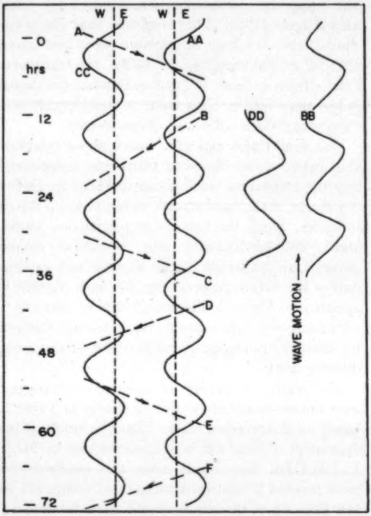

FIG. 6 – Postulated horizontal wave motion in the Straits

to gain anticyclonic vorticity. This vorticity change pattern is in accord with observations showing an intense cyclonic shear off Miami, an average current axis some $\frac{1}{3}$ the distance from Miami to Cat Cay, and a broad region of anticyclonic shear east of the axis. *Stommel* [1953], on the basis of conservation of absolute vorticity, had suggested vertical shrinking of the water column as the cause for the broad region of anticyclonic shear.

The net surface transverse flow requires a return flow at greater depths; for this circumstance, LSS find, the GEK would give actual speed. This relationship is used as a further check on the validity of the present data. From Tables 2 and 3, the speed of the net transverse surface component for Positions 2 and 3 are −2 and 4 cm/s respectively; this divergence, if extending to 100-m depth, would require an upwelling of 0.07 cm/s, a magnitude pushing the upper limit of plausibility. Again, the GEK values are consistent with other considerations.

The irregular appearance of Figure 3 is due, in part, to wind difference and, in part, to the coarse wind drift and windage corrections. Nevertheless, Figures 2 and 3 strongly suggest frequent direction changes in the transverse component, though one cannot ascribe simple periodicity to them. The data of G5618 appear most readily explained if periodicity were assumed. Let the solid curve AA in Figure 6 be the assumed horizontal transverse motion at a fixed locality, drawn with a 12-lunar-hr period and with the indicated asymmetry corresponding to greater frequency and magnitude of eastward component east of 79° 55′ W long. The short dashed lines marked A, C. . . F, correspond to the transects listed in Table 5. Thus during transect C, eastward components are encountered all the way, while during F, eastward components encountered near Cat Cay became westward near Miami. If only the trend of east-west components is considered, one finds a good correspondence between observed and postulated.

For convenience, the curve AA was drawn as a sine curve and the zero reference then displaced. For the zone west of 79° 55′, zero reference is displaced eastward as in curve CC. Figure 6. When a uniform northward component is added vectorially to these transverse components, one obtains wavy streamlines as schematically illustrated by curves BB and DD for their respective zones.

The salinity section of G5618 was executed between transects A and C. There was a 5.6-hr rest between the last GEK of transect A and the first hydrographic station. The hydro-section lasted 11 hr and was followed by an 8.2-hr rest. The resulting section, Figure 4, is not typical. Comparison with a typical one [for example, *Sverdrup* and others, 1946, Fig. 184] shows that instead of the single continuous salinity maximum tapering off westward, there are two maxima in the present section. The eastern maximum is the dominant one; but, off Miami, there is a distinct secondary high. Since the first and last stations were occupied near a westernmost displacement in the horizontal wave (the spatial relation of this hydro-section to the phases of the postulated waves is indicated by the dashed line B in Figure 6), it is likely that the westward displacement of the eastern maximum and the appearance of the separate maximum off Miami are advected there by the horizontal wave. (Here, non-synoptic data and divergence complicated the pattern.) Further, the surface transverse motion is seen extending to 150 or 200 m.

A return flow at greater depths as in internal waves appears likely for two reasons. First, the magnitude of the transverse component seems sufficiently large to expect the potential generated by the surface motion to be nullified completely by an opposite potential generated by reverse flow in lower layers. The average and maximum magnitudes (Tables 5 and 6) agree very closely with those of Pillsbury, reported by *Stommel* [1955]. Second, if return flow is non-existent, the motion would require a sea surface fluctuation whose amplitude may be estimated. The transverse component u may be taken as

$$u = 20(x/19 \times 10^5) \cos(2\pi t/T) \qquad (14)$$

obtained by assuming a linear decrease from 20 cm/s at station A, to 0 off Miami, 19 km away. Substituting (14)

$$\partial s/\partial t = -h(\partial u/\partial x) \qquad (15)$$

where s is the sea surface, setting h as 150 m, and integrating over a quarter period (3 hr), one obtains an amplitude of over 30 ft, twenty times that observed. It would appear that the fact of return flow may be confirmed or denied readily by bathythermograph lowerings near Stations A and B. Unfortunately, the situation is complicated by transport changes, wind mixing, and position uncertainty in a region of strong horizontal thermal gradient.

The salinity pattern of Figure 4 strongly resembles one reported by *Parr* [1937, Fig. 13] for hour 12. Parr suggested transverse extrusion for the western salinity maximum with a 12-lunar-hr period. *Stommel* [1955] reporting on surface current measured by Pillsbury, noted current direction of the "same sign tend to occur in blocks of 2 to 16-hour duration." Considering sampling errors and complexity of nature, it is probable that these features are actually aspects of the same phenomenon. The relation of this phenomenon to the fine structure and meandering behavior of the Gulf Stream System [*von Arx* and others, 1955; *O'Hare* and others, 1954; and others] is very suggestive. But further study is indicated, since more than speculation is desired.

If the Florida Straits is considered as a channel connecting two large basins, *Wertheim* [1953], the Atlantic with its semi-diurnal tides and the Gulf of Mexico with its predominant diurnal tides, then physical forces are present to impress on the Florida Current constituent periods of 12 and 24 lunar hr. The different apparent periods in Figures 2 and 3 may correspond to changing amplitude and phase relationships in the two primary periods while the northward wave motion assumed in Figure 6 could have been initiated by tidal phenomena transmitted through the Old Bahama Channel. It may be significant that the free periods of internal waves in a two-layer system on a rotating Earth for the average conditions of the Straits off Miami and Key West are 12 and 19 hr.

Conclusion—The pattern of transverse component of the GEK current reflects the pattern of the actual surface transverse component of the Florida Current. Two constituents of the transverse component are established. Both involve a return flow at greater depths, and both are unrelated to direct tidal stream and local winds. One constituent is an integral part of internal seiches with its surface current reversing direction every 8 to 16 hours. The other is a diverging surface transverse flow in the free stream apparently caused by boundary friction.

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Computation of the Ocean-Wave Forces on Inclined Cylinders*

L. E. BORGMAN

Abstract—After a review of the assumptions in the wave force formula for vertical cylinders proposed by *Morison, O'Brien, Johnson,* and *Schaaf* [1950], a formula embodying the same assumptions is advanced for the determination of the wave forces on an arbitrarily oriented cylinder. Essentially the x components of the water-particle velocity and acceleration in the vertical-cylinder formula are each replaced by the component of the vector (velocity or acceleration) which is perpendicular to the cylinder axis and in the plane common to the vector and the cylinder axis. The resulting equation is expressed in vector and matrix notation. A concise computational procedure which allows the use of either variable or constant coefficients is outlined and a sample calculation is provided.

Introduction—Formulas for the ocean-wave forces on vertical cylinders have been investigated considerably during the past several years. The most widely used formula growing out of this effort is that proposed by *Morison, O'Brien, Johnson,* and *Schaaf* [1950] (hereafter referred to as MOJS). This equation has been extensively applied both in the interpretation of experimental data and in the prediction of wave forces. Unfortunately, no corresponding formula has been developed and tested for the analysis of wave forces on inclined cylinders. In the following discussion, we will generalize the MOJS formula so that it will apply to cylinders arbitrarily inclined in three dimensions and will then develop mathematical techniques facilitating computation with this generalization.

Formula for wave forces on vertical piling—The MOJS formula (ignoring end effects) is

$$f_x = C_D \frac{w}{2g} D v_x |v_x| + C_m \frac{w}{g} \frac{\pi D^2}{4} a_x \tag{1}$$

where the subscript x refers to the component in the direction of wave propagation, f is the force per unit length of cylinder, C_D and C_m are the drag and inertial coefficients respectively, w is the specific weight of the fluid, g is the acceleration due to gravity, D is the cylinder diameter, and v and a are the water particle velocities and accelerations respectively. The symbol $|v_x|$ denotes the positive numerical value of v_x. We note that the formula tacitly assumes that the force on a vertical pile is a function solely of the horizontal components of the water-particle velocity and acceleration. The actual velocity and acceleration vectors are not necessarily horizontal and indeed achieve this condition only at the wave crest and at the trough. In essence, as illustrated in Figure 1, the method assumes that the total acceleration and velocity vectors represented in the figures by the vector $\mathbf{p}$ can be resolved into a horizontal component which is perpendicular to the cylinder axis and a vertical component which is parallel to the cylinder. The force on the pile is considered to be a function solely of the normal component.

Formula for the forces on inclined cylinders—If (1) is physically correct, the above comments would rather strongly suggest that the force on a cylinder which is randomly oriented could be computed in an analogous way using the component of the velocity and acceleration perpendicular to the cylinder axis and ignoring the component parallel to the cylinder axis. This hypothesis has been partially verified in a series of experiments conducted at the David Taylor Model Basin [*Pode*, 1950] to determine the hydrodynamic forces on an inclined cable under steady flow conditions. These studies showed that the force, which acts in a direction perpendicular to the cable, could be represented by

$$f = C_D \frac{w}{2g} D v^2 \sin^2 \phi \tag{2}$$

where ϕ is the angle between the velocity vector and the cable axis. But since $v \sin \phi$ is equal to the component of the velocity normal to the cylinder axis, the formula may be rewritten as

$$f = C_D \frac{w}{2g} D v_n^2 \tag{3}$$

During the course of the work at the Model Basin the magnitude of the force on the cable caused by the flow component parallel to the cable axis was

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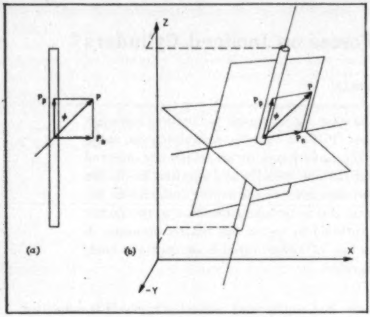

FIG. 1 – Geometrical aspects of (a) vertical and (b) randomly inclined cylinders

also determined. The axial force was found to have a magnitude less than two per cent of the perpendicular force, which indicated, as previously supposed, that the parallel flow components could be ignored in calculations. *Watson* [1953] independently checked the use of the $\sin^2 \phi$ term for the force expression in a series of towing tests on submerged wooden dowels. He obtained excellent agreement with the formula used in the Model Basin studies.

Although the experiments cited were performed only for the drag force in steady flow, it is very likely that the axial forces are also negligible in unsteady flow on smooth piling. If we make this assumption, the MOJS formula can be rewritten for the case of a randomly oriented cylinder as

$$\mathbf{f} = C_D \frac{w}{2g} D \mathbf{v}_n v_n + C_M \frac{w}{g} \frac{\pi D^2}{4} \mathbf{a}_n \tag{4}$$

In (4) $\mathbf{v}_n$ is defined as $v_n \mathbf{Q}$, where $\mathbf{Q}$ is a unit vector (see Fig. 1 where $\mathbf{p}_n$ may be interpreted as $\mathbf{v}_n$) which is both in the plane perpendicular to the cylinder axis and in the plane common to the velocity vector $\mathbf{v}$ and the cylinder axis, and which is chosen so that $\mathbf{Q} \cdot \mathbf{v} \geqq 0$. The vector $\mathbf{a}_n$ is defined in an analogous way.

Computation of $\mathbf{v}_n$ *,* v_n *, and* $\mathbf{a}_n$—In order to use (4), we need a convenient computational method for determining $\mathbf{v}_n$, v_n , and $\mathbf{a}_n$. Methods using vector and matrix notation are available for this purpose. We define $\mathbf{c}$ as a unit vector directed either up or down the cylinder axis; $\mathbf{v}$ and $\mathbf{a}$ are the water-particle velocity and acceleration respectively. In the following formulas we denote $\mathbf{v}$, $\mathbf{a}$, and $\mathbf{c}$ both in vector and matrix notation as

$$\left.\begin{array}{lll} \mathbf{v} = v_x\mathbf{i} + v_y\mathbf{j} + v_z\mathbf{k}, & \text{or} & (v) = (v_x , v_y , v_z) \\ \mathbf{a} = a_x\mathbf{i} + a_y\mathbf{j} + a_z\mathbf{k}, & \text{or} & (a) = (a_x , a_y , a_z) \\ \mathbf{c} = c_x\mathbf{i} + c_y\mathbf{j} + c_z\mathbf{k} & & \end{array}\right\} \tag{5}$$

where **i**, **j**, and **k**, are unit vectors parallel to the x, y, and z axes respectively.

Representation by vector algebra—By elementary vector algebra and the relation $c_x^2 + c_y^2 + c_z^2 = 1$, for direction cosines,

$$\begin{aligned} \mathbf{v}_n &= \mathbf{c} \times (\mathbf{v} \times \mathbf{c}) \\ &= [v_x - c_x(c_xv_x + c_yv_y + c_zv_z)]\mathbf{i} \\ &\qquad + [v_y - c_y(c_xv_x + c_yv_y + c_zv_z)]\mathbf{j} \\ &\qquad + [v_z - c_z(c_xv_x + c_yv_y + c_zv_z)]\mathbf{k} \end{aligned} \tag{6}$$

$$v_n = \{v_x^2 + v_y^2 + v_z^2 - (c_xv_x + c_yv_y + c_zv_z)^2\}^{\frac{1}{2}} \tag{7}$$

$$\begin{aligned} \mathbf{a}_n &= [a_x - c_x(c_xa_x + c_ya_y + c_za_z)]\mathbf{i} \\ &\qquad + [a_y - c_y(c_xa_x + c_ya_y + c_za_z)]\mathbf{j} \\ &\qquad + [a_z - c_z(c_xa_x + c_ya_y + c_za_z)]\mathbf{k} \end{aligned} \tag{8}$$

Representation by matrices—The representations by vectors, while leading to an explicit algebraic equation for $\mathbf{a}_n$, $\mathbf{v}_n$, and v_n , are not very convenient for computation and are useful mainly as suggesting a formulation of the problem in terms of matrices. This development is suggested by the relationship

$$\mathbf{p} \times \mathbf{c} = (p_x , p_y , p_z) \begin{Bmatrix} 0 & -c_z & c_y \\ c_z & 0 & -c_x \\ -c_y & c_x & 0 \end{Bmatrix} \tag{9}$$

where the standard 'row by column' multiplication of the matrices [*Birkhoff* and *MacLane*, 1953, p. 209 ff] is indicated. Then

$$\begin{aligned} \mathbf{c} \times (\mathbf{p} \times \mathbf{c}) &= -(\mathbf{p} \times \mathbf{c}) \times \mathbf{c} \\ &= -(p_x , p_y , p_z) \cdot \\ &\qquad \begin{Bmatrix} 0 & -c_z & c_y \\ c_z & 0 & -c_x \\ -c_y & c_x & 0 \end{Bmatrix} \begin{Bmatrix} 0 & -c_z & c_y \\ c_z & 0 & -c_x \\ -c_y & c_x & 0 \end{Bmatrix} \\ &= (p_x , p_y , p_z) \cdot \begin{Bmatrix} 1 - c_x^2 & -c_xc_y & -c_xc_z \\ -c_xc_y & 1 - c_y^2 & -c_yc_z \\ -c_xc_z & -c_yc_z & 1 - c_z^2 \end{Bmatrix} \end{aligned} \tag{10}$$

If (C) is the 3×3 matrix

$$(C) = \begin{Bmatrix} 1 - c_x^2 & -c_xc_y & -c_xc_z \\ -c_xc_y & 1 - c_y^2 & -c_yc_z \\ -c_xc_z & -c_yc_z & 1 - c_z^2 \end{Bmatrix}$$

Then the formula for $\mathbf{v}_n$, v_n , and $\mathbf{a}_n$ in matrix form becomes

$$(v_n) = (v_{nx} , v_{ny} , v_{nz}) = (v)(C) \tag{11}$$

$$v_n = \{(v_n)(v_n)^T\}^{\frac{1}{2}} \tag{12}$$

$$(a_n) = (a_{nx} , a_{ny} , a_{nz}) = (a)(C) \tag{13}$$

where $(v_n)^T$ denotes the transpose of (v_n).

Total combined force on a cylinder—In normal practice, several points along the axis of the cylinder are selected and the force per foot is computed at each point. The total force on the cylinder can then be determined by numerical integration along the cylinder axis. This whole procedure can be concisely stated in terms of matrix algebra.

As a convention to avoid writing unnecessary zeros, we formally define square brackets to mean

$$\begin{bmatrix} b_1 \\ b_2 \\ b_3 \\ \cdot \\ \cdot \\ \cdot \\ b_m \end{bmatrix} = \begin{Bmatrix} b_1 & 0 & 0 & \cdots & 0 \\ 0 & b_2 & 0 & \cdots & 0 \\ 0 & 0 & b_3 & \cdots & 0 \\ \cdot & \cdot & \cdot & & \cdot \\ \cdot & \cdot & \cdot & & \cdot \\ \cdot & \cdot & \cdot & & \cdot \\ 0 & 0 & 0 & \cdots & b_m \end{Bmatrix} \tag{14}$$

Multiplication by a column of elements in square brackets proceeds exactly as though the corresponding diagonal matrix were being used.

If m points along the cylinder axis are selected for computation, the formula is

$$\begin{Bmatrix} f_{x1} & f_{y1} & f_{z1} \\ f_{x2} & f_{y2} & f_{z2} \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ f_{xm} & f_{ym} & f_{zm} \end{Bmatrix} = C_D \frac{w}{2g} D \begin{bmatrix} |v_{n1}| \\ |v_{n2}| \\ \cdot \\ \cdot \\ \cdot \\ |v_{nm}| \end{bmatrix} \cdot \begin{Bmatrix} v_{x1} & v_{y1} & v_{z1} \\ v_{x2} & v_{y2} & v_{z2} \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ v_{xm} & v_{ym} & v_{zm} \end{Bmatrix} \begin{Bmatrix} 1 - c_x^2 & -c_xc_y & -c_xc_z \\ -c_xc_y & 1 - c_y^2 & -c_yc_z \\ -c_xc_z & -c_yc_z & 1 - c_z^2 \end{Bmatrix}$$
$$+ C_M \frac{w}{g} \frac{\pi D^2}{4} \begin{Bmatrix} a_{x1} & a_{y1} & a_{z1} \\ a_{x2} & a_{y2} & a_{z2} \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ a_{xm} & a_{ym} & a_{zm} \end{Bmatrix} \cdot \begin{Bmatrix} 1 - c_x^2 & -c_xc_y & -c_xc_z \\ -c_xc_y & 1 - c_y^2 & -c_yc_z \\ -c_xc_z & -c_yc_z & 1 - c_z^2 \end{Bmatrix} \tag{15}$$

In the above formula, the kth row in each matrix represents the variable at the kth point along the cylinder axis. That is, (v_{xk}, v_{yk}, v_{zk}) and (a_{xk}, a_{yk}, a_{zk}) respectively are the components of the water-particle velocity and acceleration vectors at the kth point. Similarly (f_{xk}, f_{yk}, f_{zk}) are the force per unit length in the x, y, and z directions, respectively, at the kth point. The matrix $[|v_{ni}|]$ is a function of the matrix product, $(v_i)(C)$. In particular, since

$$\begin{Bmatrix} v_{nx1} & v_{ny1} & v_{nz1} \\ v_{nx2} & v_{ny2} & v_{nz2} \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ v_{nxm} & v_{nym} & v_{nzm} \end{Bmatrix} = \begin{Bmatrix} v_{x1} & v_{y1} & v_{z1} \\ v_{x2} & v_{y2} & v_{z2} \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ v_{xm} & v_{ym} & v_{zm} \end{Bmatrix} \cdot \begin{Bmatrix} 1 - c_x^2 & -c_xc_y & -c_xc_z \\ -c_xc_y & 1 - c_y^2 & -c_yc_z \\ -c_xc_z & -c_yc_z & 1 - c_z^2 \end{Bmatrix} \tag{16}$$

the ith element of $[|v_{ni}|]$ is

$$|v_{ni}| = \sqrt{v_{nxi}^2 + v_{nyi}^2 + v_{nzi}^2} \tag{17}$$

The total force may be determined by numerical integration down the columns of (f_i) in (15).

Variable coefficients—One additional generalization of (15) is possible. Some of the recent experiments seem to indicate that C_D and C_M are variables and might, in some manner, be functions of Reynolds number, Iverson's modulus, or other quantities. The formula can be easily modified to include variable coefficients as

$$\begin{Bmatrix} f_{x1} & f_{y1} & f_{z1} \\ f_{x2} & f_{y2} & f_{z2} \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ f_{xm} & f_{ym} & f_{zm} \end{Bmatrix} = \frac{w}{2g} \begin{bmatrix} C_{D1} \\ C_{D2} \\ \cdot \\ \cdot \\ \cdot \\ C_{Dm} \end{bmatrix} \begin{bmatrix} D\,|v_{n1}| \\ D\,|v_{n2}| \\ \cdot \\ \cdot \\ \cdot \\ D\,|v_{nm}| \end{bmatrix} \cdot \begin{Bmatrix} v_{x1} & v_{y1} & v_{z1} \\ v_{x2} & v_{y2} & v_{z2} \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ v_{xm} & v_{ym} & v_{zm} \end{Bmatrix} \begin{Bmatrix} 1 - c_x^2 & -c_xc_y & -c_xc_z \\ -c_xc_y & 1 - c_y^2 & -c_yc_z \\ -c_xc_z & -c_yc_z & 1 - c_z^2 \end{Bmatrix}$$
$$+ \frac{w}{g} \frac{\pi D^2}{4} \begin{bmatrix} C_{M1} \\ C_{M2} \\ \cdot \\ \cdot \\ \cdot \\ C_{Mm} \end{bmatrix} \begin{Bmatrix} a_{x1} & a_{y1} & a_{z1} \\ a_{x2} & a_{y2} & a_{z2} \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ a_{xm} & a_{ym} & a_{zm} \end{Bmatrix} \cdot \begin{Bmatrix} 1 - c_x^2 & -c_xc_y & -c_xc_z \\ -c_xc_y & 1 - c_y^2 & -c_yc_z \\ -c_xc_z & -c_yc_z & 1 - c_z^2 \end{Bmatrix} \tag{18}$$

After computing $(v_i)(C)$, $|v_{ni}|$ is computed by (17) and multiplied by D to obtain the ith element in $[D\,|v_{ni}|]$. Since the Reynolds number for sea water is approximately $10^5 D\,|v_n|$, the elements in $[D\,|v_{ni}|]$ essentially give the Reynolds numbers along the pile. $[C_{Di}]$ can now be determined by whatever variable curves have been previously selected. The computation of the inertial forces proceeds in an analogous fashion except there is no matrix corresponding to $[D \mid v_{ni} |]$; however a subsidiary matrix, $[| a_{ni} |]$, may be computed in a manner similar to (17) if it is desired to make C_M depend on the magnitude of the normal acceleration in some way.

Simplifications caused by zero columns and rows—In most computations, a two-dimensional wave theory is used to calculate **v** and **a**. In this case, one of the columns in each of the matrices (v) and (a) will consist entirely of zero elements. Alternately, one of the rows in the (C) matrix may be composed entirely of zeros for certain orientations of the cylinder. In either case, it is unnecessary to write down the column or row of zeros since they never affect the answer. If jth column in (v_i) or (a_i) is zero, the jth row in the (C) matrix by which it is to be multiplied may be crossed out. Similarly, if the jth row in (C) is zero, the jth column in (a_i) and (v_i) may be crossed out.

Sample calculation—To illustrate the foregoing, a computation will be made of the forces on a 2-ft dia cylinder, 42.5 ft long, with direction cosines $c_x = 0.551$, $c_y = 0.122$, and $c_z = 0.826$. We assume that three points along the cylinder will determine the total force with sufficient accuracy. Furthermore, we suppose that the (v_i) and (a_i) matrices are

$$(v_{xi}, v_{yi}, v_{zi}) = \begin{Bmatrix} 12.5 & 0 & 0.2 \\ 12.5 & 0 & 2.9 \\ 10.9 & 0 & 8.3 \end{Bmatrix} \text{ ft/sec}$$

$$(a_{xi}, a_{yi}, a_{zi}) = \begin{Bmatrix} 1.4 & 0 & -0.7 \\ 4.7 & 0 & -2.0 \\ 9.7 & 0 & +2.8 \end{Bmatrix} \text{ ft/sec}^2$$

The matrix (C) is given by

$$(C) = \begin{Bmatrix} 0.696 & -0.067 & -0.455 \\ -0.067 & 0.985 & -0.101 \\ -0.455 & -0.101 & 0.318 \end{Bmatrix}$$

To illustrate the procedure for both variable and fixed coefficients, we will use the steady state C_D as a function of the Reynolds number [*Rouse*, 1950, p. 124] and a fixed C_M value of 1.5. Then the relevant parts of (15) and (18) give the formula as

$$\begin{Bmatrix} f_{x1} & f_{y1} & f_{z1} \\ f_{x2} & f_{y2} & f_{z2} \\ f_{x3} & f_{y3} & f_{z3} \end{Bmatrix} = \frac{w}{2g} [C_{Di}][D|v_{ni}|] \begin{Bmatrix} 12.5 & 0.2 \\ 12.5 & 2.9 \\ 10.9 & 8.3 \end{Bmatrix}$$

$$\cdot \begin{Bmatrix} 0.696 & -0.067 & -0.455 \\ -0.455 & -0.101 & 0.318 \end{Bmatrix} + C_M \frac{w}{g} \frac{\pi D^2}{4}$$

$$\cdot \begin{Bmatrix} 1.4 & -0.7 \\ 4.7 & -2.0 \\ 9.7 & +2.8 \end{Bmatrix} \begin{Bmatrix} 0.696 & -0.067 & -0.455 \\ -0.455 & -0.101 & 0.318 \end{Bmatrix}$$

$$= 0.993 \begin{bmatrix} 0.36 \\ 0.36 \\ 0.33 \end{bmatrix} \begin{bmatrix} 20.6 \\ 17.6 \\ 9.5 \end{bmatrix} \begin{Bmatrix} 8.61 & -0.86 & -5.62 \\ 7.38 & -1.13 & -4.77 \\ 3.81 & -1.57 & -2.32 \end{Bmatrix}$$

$$+ 9.37 \begin{Bmatrix} 1.29 & -0.02 & -0.86 \\ 4.18 & -0.11 & -2.77 \\ 5.48 & -0.93 & -3.52 \end{Bmatrix}$$

$$= \begin{Bmatrix} 63.4 & -6.3 & -41.4 \\ 46.4 & -7.1 & -30.0 \\ 11.8 & -4.9 & -\ 7.2 \end{Bmatrix} + \begin{Bmatrix} 12.1 & -0.2 & -\ 8.1 \\ 39.2 & -1.0 & -26.0 \\ 51.3 & -8.7 & -33.0 \end{Bmatrix}$$

$$= \begin{Bmatrix} 75.5 & -\ 6.5 & -49.5 \\ 85.6 & -\ 8.1 & -56.0 \\ 63.1 & -13.6 & -40.2 \end{Bmatrix} \text{ lb/ft}$$

The total force on the cylinder is then, by trapezoidal rule integration,

$$(F_x, F_y, F_z) = (3292, -386, -2143) \text{ lb.}$$

Concluding remarks—Although the formula presented is a speculative extension of the MOJS formula to three dimensions and will require experimental verification before it can be used with confidence, the methods of computation shown should be useful in any three-dimensional wave-force formula. An analogous generalization can easily be prepared, for instance, for the formula outlined by *Crooke* [1955] which uses Iverson's modulus. Indeed the general methods presented should be useful in a wide variety of three-dimensional fluid-flow problems, both for steady-state conditions and for continually varying systems.

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The Equilibrium Beach

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Abstract—The equilibrium beach has curvature and sand-prism characteristics adjusted to each other so delicately that the potential littoral motion provides precisely the energy needed to transport the detritus supplied at the up-current end. The time element in this balance is long-term rather than instantaneous. A beach which performs in any other way is not in equilibrium. The maintenance of certain beaches in equilibrium form is of great economic or political importance. The most pressing case of inequilibrium is that of the rapidly retrograding beach. In many instances the beach can be restored to an equilibrium condition by decreasing the actual littoral drift or increasing the available supply of sand.

The concept of the graded stream is basic to an understanding of river behavior. *Mackin* [1948] has summarized the idea clearly, with several excellent examples. *Leopold* and *Miller* [1956] have detailed certain aspects of the concept. A simple definition, modified from Mackin, may be given as follows:

The graded stream has slope and channel characteristics adjusted to each other so delicately that the available discharge provides precisely the energy needed to transport the bed load supplied from the drainage basin. The time element in this balance is long-term rather than instantaneous. The balance is so arranged that an alteration in any one of the controlling factors will shift the equilibrium enough to absorb the effect of the change. A stream which performs in any other way is not graded. The changes which a graded stream may make, in order to maintain such a balance, include alteration of: (1) gradient, (2) tortuosity, (3) hydraulic radius, and (4) channel roughness. (But these four are not to be thought of as equal in effect or likelihood.) The same idea is used by engineers who refer to 'poised' or 'regime' streams [*Blench*, 1957, pp. 2–3].

A similar concept can be applied, with good advantage, to beaches and other types of coast line [*Schijf*, 1957]. The term 'equilibrium beach,' however, should not be considered a duplicate of the term 'equilibrium profile.' The latter is taken at right angles to the coast line, and considered in a vertical plane. The former should be taken parallel with the coast line and examined in a horizontal plane.

The analogy with the graded river can be made clearer if the river channel is said, at any given spot, to have elevation rather than gradient. When the gradient is altered, the elevation is generally changed. The beach also has a 'convergence' or 'gradient' which lies, however, in a horizontal plane. We find it difficult to visualize because we have no convenient reference plane to which it is asymptotic, such as that furnished by sea level for the river profile. There is, however, a vertical plane containing a horizontal line with which the shoreline tends to converge. This horizontal line might be called the 'ultimate shoreline.' Its orientation, and therefore the angle of convergence with the actual shoreline, may be estimated, in some instances, from the maximum fetch and the wave resultant [*Guilcher*, 1958]. The calculated angle will generally be quite small. The suggestion that the river bed be said to have elevation, that is, vertical position, leads to the observation that the beach has position in a horizontal plane. Hence its 'convergence' with the 'ultimate shoreline' can be seen in some of the curves which we observe in map view. The chief differences between the stream gradient, and the beach 'convergence' or curvature, are:

River gradient	Shore-line 'convergence' or curvature
Lies in vertical plane	Lies in horizontal plane
Has sea level as a reference plane	Has no obvious reference plane
Gradient reversals result in ponding	Local ponding does not occur

A beach can be studied in terms of the sediment introduced at one end, and removed at the other. The two quantities are not necessarily equal. Sediment may be lost by deflation inland (that is, as sand dunes), or by seaward drift across the continental shelf; in either instance, the volume of sediment introduced exceeds the volume of sediment delivered. On the other hand, additional sediment may be acquired from the land (that is, by rivers or rain-wash) or from the sea floor; for such conditions, the volume of sediment introduced is less than the volume delivered. There is also a third pair of possibilities: the coast may be retrograded (moved, horizontally, toward the land), or prograded (moved, horizontally, toward the sea), to offset an excess or deficit of sediment. It is possible, of course, to have a seventh possibility: the two volumes of sediment are equal, and there is no change in the position of the shoreline.

These seven conditions, and their various combinations, are derived from the fact that the beach, like the granular material on many river beds, is in constant motion. It is more free to move in either direction than is river bed-load, but, like the river detritus, it commonly moves eventually in a single direction. (The transporting energy is in general derived from wind-driven waves, rather than from gravity; hence the greater freedom in direction.)

River bed load lies as fill in a more-or-less U-shaped channel. Its lower surface is fixed by the shape of the maximum flood channel, its upper surface during low-water stages. The beach likewise lies on an eroded surface, cut during times of high tides and high waves. Its upper surface is shaped, most of the time, by relatively quiet waters. The lower, cut, surface exhibits, in cross section, an equilibrium profile for storm conditions. The upper, deposited, surface exhibits, in cross section, an equilibrium profile for calm conditions. The beach is the prism of moving sand which lies, at any given instant, between these two surfaces. If the quantity of sand in this prism is relatively great, seasonal and other short-term changes in transportation can be absorbed without altering the character of the beach.

The beach has 'convergence' or 'curvature' in a horizontal plane, energy in a single net direction, and a prism of sediments in transport. It has, in addition, other characteristics of an alluvial river, such as sediment surface roughness. It does not have tortuosity (in a plane at right angles to the plane containing the 'convergence') comparable with the meanders of a river. Nor does it have hydraulic radius. Instead, the beach has steepness (which varies with, among other things, sediment grain size).

The channel characteristics of a river include its tortuosity, hydraulic radius, and roughness. The prism characteristics of a beach include its steepness, thickness, and roughness.

The similarities of the two systems are considerable. Both result from directed streams of moving water. Hence the concept of an equilibrium beach may be fruitful. A definition might be offered as follows:

The equilibrium beach has curvature and sand prism characteristics adjusted to each other so delicately that the potential littoral motion provides precisely the energy needed to transport the detritus supplied at the up-current end. The time element in this balance is long-term rather than instantaneous. A beach which performs in any other way is not in equilibrium.

Under such a definition, a pocket beach does not attain an equilibrium configuration before it succeeds in filling its indentation. Likewise, a shoreline composed exclusively of bare rocks does not have an equilibrium curvature.

The problems of beach control can be evaluated in the light of the concept of the equilibrium beach. A shoreline which migrates rapidly landward does so because not enough sediment is introduced at the up-current end to absorb all the energy provided by the potential littoral drift. It is not an equilibrium shoreline. A river of similar nature scours its bed, over a long term, because it has an excess of gravitational energy. Such a river is generally considered to be, geologically, youthful, regardless of its chronologic age or its past history. In this sense, the beach is immature, or sub-mature, or rejuvenated.

The associated political, social, and economic problems may be enormous. The east coast of Florida has, today, such a shoreline. It is migrating landward because of a deficit of detritus for southward transportation. In the past, efforts have been made to correct the situation by building groynes and other similar installations. It should be obvious that there are only two ultimate solutions: decrease the net unidirectional energy, or increase the amount of sediment available. The former is, at present, unthinkable. The latter can be handled, at least temporarily, by pumping sand in from adjacent areas. Such a program is now being studied [*Bruun*, 1957]. Groynes may provide a partial solution by absorbing some of the wave energy, thus permitting a more leisurely littoral drift, and therefore increasing the amount of time spent by each sand grain in transit along a given stretch of beach.

A shoreline which migrates seaward does so because the detritus introduced at the up-current end exceeds the amount which can be delivered at the opposite end. The economic problems involved are, perhaps, not so acute as those associated with a retrograding shore.

The concept of the equilibrium shoreline suggests several possible solutions, one of which would require soil conservation measures inland from the up-current area. The reverse (soil erosion measures to control a landward migrating beach) does not seem generally attractive.

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Seepage of Steady Rainfall through Soil into Drains*

DON KIRKHAM

Abstract—Theoretical formulas for the height of all points of an arch-shaped water table are derived for steady rainfall seeping into homogeneous soil drained by tubes or ditches. The soil is underlain by an impermeable layer and the drains are taken to be equally spaced and equally deep. The solution is based on exact mathematical procedures, but utilizes a physical assumption that the height of the water table as measured from a reference plane passing through the lowest points of the water table is small compared to the depth of the impermeable layer. For tube drains running half full and when the impermeable layer is at great depth, the theoretical height H of the water table midway between drain tubes takes the particularly simple form, $H = (2sR/\pi k)\ln(2s/\pi r)$ where H is height above the reference plane, $2r$ is the diameter of the drain tube, $2s$ is the spacing between drain tubes, R is the rainfall rate, and k the hydraulic conductivity. Flow nets for tube and ditch drainage are presented; a table for making practical computations has been prepared. The theory is compared with field data of Kirkham and De Zeeuw; good agreement was obtained. Finally, the interesting point is brought out that the Dupuit-Forchheimer (DF) theory emerges from the general theory for the special case of very large ratio of drain spacing to height of water saturated soil and for an essentially flat water table. Thus the analysis presents a rational foundation for DF theory which has heretofore been lacking.

Statement of problem—In Figure 1a, equally spaced ditches in soil remove ground water at a steady rate equal to that of a steady rain. Evaporation is negligible and an impermeable layer prevents deep seepage. The ditches are narrow and are assumed to have water in them to the level E where the arch-shaped water table EDE intercepts them. A surface of seepage at E will be very small and is neglected. The water table, as is generally true, has small curvature; also, the distance CD is small compared to the depth CB.

It is a purpose of this paper to obtain, for Figure 1a, analytic expressions for the stream and potential functions, and hence flow nets, for the water seeping into the drains; also, to obtain an analytical expression relating the height of the water table, at all points on its profile, to the parameters, depth and spacing of ditches, depth of the impermeable layer, rate of rainfall, and hydraulic conductivity of the soil. It is a further purpose to obtain an analytical expression for the rate of fall of the water table midway between drains at the instant that the rainfall ceases. Finally, it is our purpose to obtain all the analytical solutions mentioned above, when the rain seeping into the soil, instead of being removed by ditches as in Figure 1a, is removed by other types of 'sinks,' including tube (tile) drains. For the moment we shall consider further the ditch case of Figure 1a

Physical approximations—We could conceivably solve the problem of Figure 1a exactly, by pursuing a hodograph procedure of Van Deemter discussed by *Van Schilfgaarde* and others [1956, pp. 681–695], but the analysis would be extremely complex. We accordingly seek approximate solutions based on certain simplifying physical approximations. Our mathematical analysis will be exact. The basic physical approximation is due to *Hooghoudt* [1940, pp. 555–589, esp. p. 585]. It is: the loss of hydraulic head in the arched region *EDECE* is negligible compared to the loss of head for the remainder of the flow region. Physically this means that we can replace the soil in the region *EDECE* by coarse gravel of essentially infinite conductivity, provided that we simultaneously introduce frictionless membranes of zero thickness along the streamline segments (see Fig. 1b, *LK*, *JI*, *HG*, and *DC*). Without such membranes the water in the gravel would spread out because of gravitation, and the arched form of the water table (and in particular the height *CD* we seek) could not be conceived to exist. An infinite number of membranes are needed; otherwise the arc of the water table would not be continuous.

If there is to be no loss of head in the 'gravel,' then the membranes there need not be located along the streamlines. The membranes could just as well extend vertically downward from points *LJH* in Figure 1b to the line *EC*. In this event, the streamlines would all be equally spaced along

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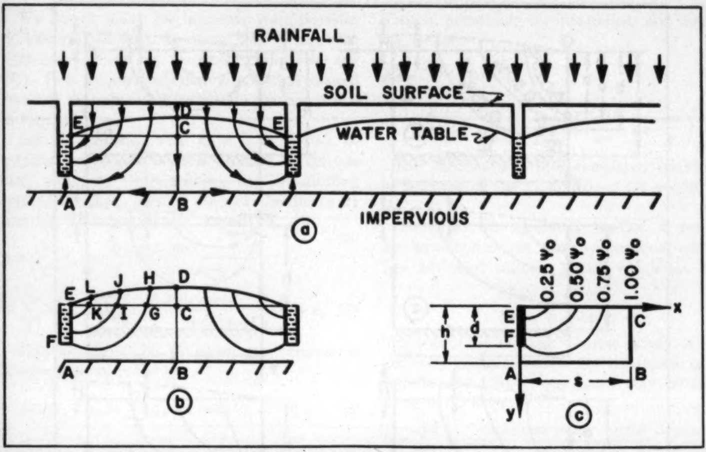

FIG. 1 – (a) Seepage of steady rainfall through soil into equally spaced ditch drains; (b) typical drainage section (c) approximate conditions for theoretical analysis; streamlines are not computed but schematic

the line *EC*, as shown in Figure 1c. We shall consider them to be so spaced. Our analysis is simplified thereby.

Our problem then can be reduced to that indicated in Figure 1c, where we let *d* be the depth of the ditch, referred to the plane *EC*; *h* the distance from *EC* to the impermeable layer and *s* the semispacing of the ditches. The ditches are initially to be taken of zero width (slits); later their finite width will be taken into account. In Figure 1c we also let the symbol ψ_0 denote the quantity of water reaching a ditch from one side per unit time per unit length of ditch. Therefore, the extreme streamline *CBAF*, entering the soil midway between ditches and leaving the soil at the bottom point *F* of the ditch, may be labelled 1.0 ψ_0; and the three other streamlines shown in Figures 1a and 1b are accordingly to be labelled 0.25 ψ_0, 0.50 ψ_0, and 0.75 ψ_0. The point *E* is a zero streamline.

If *R* is the rate of rainfall (say cubic inches per square inch of soil surface per hour, that is, inches per hour), then ψ_0 is related to *R* and the semispacing *s* by

$$\psi_0 = Rs \qquad (1)$$

Analysis

We shall determine the height *CD* of Figure 1a by first obtaining an analytical expression for the stream function ψ valid at all points in the assumed flow medium *ABCEFA* of Figure 1c, and then by determining from ψ a corresponding hydraulic head (potential) function. The latter will yield for the point *C* in Figure 1c the desired height *CD* of Figures 1a and 1b. In obtaining ψ we remember that ψ is sought not only for the ditch case of Figure 1 but for a number of other types of drainage outlets (sinks). Therefore we consider a more general problem than that of Figure 1c, a problem which will include Figure 1c as a special case. The more general problem is indicated in Figure 2a, where the sink is of vertical length $(b - a)$, with b and a as shown. Figure 2a goes over to Figure 2b by taking $a = 0$ and $b = d$. Likewise, as will later be brought out, all the situations in Figure 2 are special cases of Figure 2a.

To obtain ψ for Figure 2a, we make a further physical assumption: that the amount of water seeping into unit vertical height of slit per unit time is constant over the height of the slit. In practice this assumption would be difficult to realize because the slit would be a surface over which the hydraulic head would vary in an unrealistic manner. But the assumption does have a practical implication. A surface surrounding the slit as in Figure 2b must theoretically be a surface of equal hydraulic head. Therefore this sur-

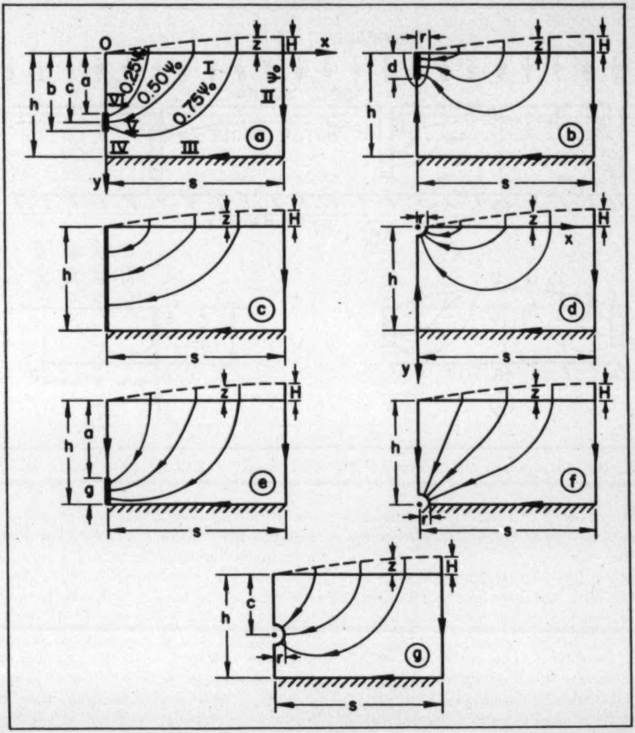

FIG. 2 – Semi-sections of seepage regions; regions are as in Fig. 1c, except that various types of sinks are included

face can be identified with an actual drain running full, as in practice. The drain must be running full, otherwise surfaces of seepage will exist over the surface and it cannot be a surface of equal hydraulic head.

Development of stream and potential functions—We have let ψ denote the stream function. We now further let ϕ be the hydraulic head and Φ a velocity potential related to ϕ by

$$\Phi = k\phi \tag{2}$$

We shall choose Φ such that $\phi = 0$ at $y = 0$ in Figure 2a. That is, the x axis as shown will be the reference level for hydraulic head, and the distance z in Figure 2 will accordingly be given by ϕ, when ϕ is evaluated at $x = x$ and $y = 0$. The height H in Figure 2 will be given by ϕ when $x = s$ and $y = 0$.

The functions ψ and Φ, in order to be correct, must satisfy the differential equations

$$\partial^2\psi/\partial x^2 + \partial^2\psi/\partial y^2 = 0 \tag{3}$$

$$\partial^2\Phi/\partial x^2 + \partial^2\Phi/\partial y^2 = 0 \tag{4}$$

and the boundary conditions.

The boundary conditions for ψ are:

At $y = 0$ $\Psi = (x/s)\Psi_0$ from $x = 0$ to s Cond. I
At $x = s$ $\Psi = \Psi_0$ from $y = 0$ to h Cond. II
At $y = h$ $\Psi = \Psi_0$ from $x = 0$ to s Cond. III
At $x = 0$ $\Psi = \Psi_0$ from $y = b$ to h Cond. IV
At $x = 0$ $\Psi = [(y - a)/(b - a)]\Psi_0$ from $y = a$ to b Cond. V
At $x = 0$ $\Psi = 0$ from $y = 0$ to a Cond. VI

We do not know the boundary conditions for Φ, but we can solve for them once ψ has been determined (from its boundary conditions and (3)). It is emphasized that a principal desired result is the value of $\phi = \Phi/k$ for the line $y = 0$ in Figure 2.

Let A_m and B_m, with $m = 1, 2, 3, \cdots$, be arbitrary constants, then a function ψ (as one may verify by differentiating and substituting into (3)), which satisfies (3) and Conditions II and III for any values of A_m and B_m, is

$$\psi = \sum_1^\infty A_m \sin \frac{m\pi x}{s} \frac{\sinh [m\pi(h-y)/s]}{\sinh (m\pi h/s)} + \sum_1^\infty B_m \sin \frac{m\pi(h-y)}{h} \frac{\sinh [m\pi(s-x)/h]}{\sinh (m\pi s/h)} + \psi_0 \quad (5)$$

Condition I and Eq. (5) yield, after transposing the constant ψ_0 to the left

$$(x/s)\psi_0 - \psi_0 = \sum_1^\infty A_m \sin (m\pi x/s), \quad x = 0 \text{ to } s \quad (6)$$

Therefore, consideration of the right hand side (RHS) of (6) as a Fourier sine series for the interval $x = 0$ to s yields

$$A_m = (2/s) \int_0^s [(x/s)\psi_0 - \psi] [\sin (m\pi x/s)] \, dx$$

That is

$$A_m = -2\psi_0 \pi^{-1} m^{-1} \quad (7)$$

Notice that the values of A_m are independent of the distances a, b, and h, and hence that the A_m values are the same for each case in Figure 2.

To obtain the B_m we utilize successively the remaining Conditions IV, V, and VI in (5), to find, after introducing a new variable z defined by $z = h - y$, the results

$$0 = \sum_1^\infty B_m \sin (m\pi z/h), \qquad z = 0 \text{ to } h - b$$

$$\frac{h - a - z}{b - a}\psi_0 - \psi_0 = \sum_1^\infty \sin (m\pi z/h), \qquad z = h - b \text{ to } h - a$$

$$-\psi_0 = \sum_1^\infty B_m \sin (m\pi z/h), \qquad z = h - a \text{ to } h$$

Thus, the B_m may be considered as coefficients of a Fourier sine series in the interval 0 to h, with the B_m given accordingly by

$$B_m = \frac{2}{h} \int_{h-b}^{h-a} \left[\frac{h - a - z}{b - a}\psi_0 - \psi_0 \right] \sin \frac{m\pi z}{h} \, dz + \frac{2}{h} \int_{h-a}^{h} (-\psi_0) \sin \frac{m\pi z}{h} \, dz$$

That is, performing the integrations and simplifying, we have

$$B_m = \frac{2\psi_0}{\pi} (-1)^m \cdot \left[\frac{1}{m} - \frac{h}{\pi m^2 (b - a)} \left(\sin \frac{m\pi b}{h} - \sin \frac{m\pi a}{h} \right) \right] \quad (8)$$

Our function ψ is thus completely determined by substituting the A_m and B_m of (7) and (8) into (5).

To obtain the potential function Φ from ψ, we now utilize the Cauchy-Riemann relations (see advanced calculus books) which are

$$\partial\Phi/\partial x = \partial\psi/\partial y \quad (9)$$

$$\partial\Phi/\partial y = -\partial\psi/\partial x \quad (10)$$

The sought-for function Φ must satisfy (4), (9), and (10) simultaneously. By inspection of (4), (5), (9), and (10) we see that Φ may be written down in the form

$$\Phi = \sum_1^\infty A_m \cos \frac{m\pi x}{s} \frac{\cosh [m\pi(h-y)/s]}{\sinh (m\pi h/s)} + \sum_1^\infty B_m \cos \frac{m\pi(h-y)}{h} \frac{\cosh [m\pi(s-x)/h]}{\sinh (m\pi s/h)} + C \quad (11)$$

where C is a constant to be chosen such that Φ for the lowest point on the water table will be $\Phi = k\phi = 0$. The constant C will also be associated with the finite width of an actual drainage facility, as will later be clear. One may verify by differentiation of (5) and (11) that (9) and (10) are satisfied by ψ and Φ of (5) and (11). If one did not see by inspection how to write down Φ from ψ, a method described by *Green* [1948, p. 51], involving complex variable, could be used. One may verify (by differentiation and substitution) that Φ as given by (11) satisfies (4).

Although (5) and (11) are correct, simpler forms can be obtained by trigonometric reduction. These forms are

$$\psi = \sum_1^\infty A_m \sin \frac{m\pi x}{s} \frac{\sinh [m\pi(h-y)/s]}{\sinh (m\pi h/s)} - \sum_1^\infty (-1)^m B_m \sin \frac{m\pi y}{h} \frac{\sinh [m\pi(s-x)/h]}{\sinh (m\pi s/h)} + \psi_0 \quad (12)$$

$$\Phi = \sum_1^\infty A_m \cos \frac{m\pi x}{s} \frac{\cosh [m\pi(h-y)/s]}{\sinh (m\pi h/s)} + \sum_1^\infty (-1)^m B_m \cos \frac{m\pi y}{h} \frac{\cosh [m\pi(s-x)/h]}{\sinh (m\pi x/h)} + C \quad (13)$$

RAPIDLY CONVERGENT SERIES FOR ψ AND Φ

The A_m, as given by (7), and the B_m, as given by (8), when substituted in (12) and (13), yield ψ and Φ for the case of Figure 2a. The results for ψ and Φ are rapidly converging infinite series, except, unfortunately, for values of x and y near the sinks. Since we need to know Φ near the sinks (in order to identify Φ with an equipotential surface near the sink and hence an actual drainage sink), we need to obtain rapidly converging series for the RHS of (13) for small x and y. We also need rapidly converging series for the RHS of (12) for small x and y. We consider the series for (12).

ψ for Figure 2a—Observe the following two identities for the ratios of hyperbolic terms in (12). (Proof of the first is left to the reader; the second identity may be written down by inspection of the first, once the first is obtained.)

$$\frac{\sinh [m\pi(h-y)/s]}{\sinh (m\pi h/s)} = e^{-m\pi y/s} - \frac{e^{-m\pi h/s}\sinh (m\pi y/s)}{\sinh (m\pi h/s)} \quad (14)$$

$$\frac{\sinh [m\pi(s-x)/h]}{\sinh (m\pi s/h)} = e^{-m\pi s/h} - \frac{e^{-m\pi s/h}\sinh (m\pi x/h)}{\sinh (m\pi s/h)} \quad (15)$$

Now substitute the RHS of (7) and (8), and of (14) and (15), into (12) to obtain after some rearranging

$$\frac{\pi}{2}\frac{\psi_0 - \psi}{\psi_0} = S_1 - S_2 + S_3 - S_4 - S_5 + S_6 \quad (16)$$

where

$$S_1 = \sum_1^\infty \frac{1}{m}\sin\frac{m\pi x}{s}\, e^{-m\pi y/s} \qquad \text{(use (23))} \quad (17)$$

$$S_2 = \sum_1^\infty \frac{1}{m}\sin\frac{m\pi x}{s}\,\frac{e^{-m\pi h/s}\sinh (m\pi y/s)}{\sinh (m\pi h/s)} \quad (18)$$

$$S_3 = \sum_1^\infty \frac{1}{m}\sin\frac{m\pi y}{h}\, e^{-m\pi x/h} \qquad \text{(use (24))} \quad (19)$$

$$S_4 = \sum_1^\infty \frac{1}{m}\sin\frac{m\pi y}{h}\,\frac{e^{-m\pi s/h}\sinh (m\pi x/h)}{\sinh (m\pi s/h)} \quad (20)$$

$$S_5 = \frac{h}{\pi(b-a)}\sum_1^\infty \frac{1}{m^2}\left(\sin\frac{m\pi b}{h} - \sin\frac{m\pi a}{h}\right) \cdot \sin\frac{m\pi y}{h}\, e^{-m\pi x/h} \quad (21)$$

$$S_6 = \frac{h}{\pi(b-a)}\sum_1^\infty \frac{1}{m^2}\left(\sin\frac{m\pi b}{h} - \sin\frac{m\pi a}{h}\right) \cdot \sin\frac{m\pi a}{h}\,\frac{e^{-m\pi s/h}\sinh (m\pi x/h)}{\sinh (m\pi s/h)} \quad (22)$$

In (16), S_1 and S_2 stem from terms in (12) having coefficients A_m. The remaining terms in (16) stem from terms in (12) having coefficients B_m.

The quantity S_2, as seen in the RHS of (18), sums rapidly because of the factor exp $(-m\pi h/s)$. Also, S_4 and S_6 sum extremely rapidly because of the factor exp $(-m\pi s/h)$. The sums S_1 and S_3 converge very slowly for small x and y, but this is immaterial because, as will be shown in the Appendix (see there Eq. (96) and below), the sums S_1 and S_3 can be obtained in the closed forms

$$S_1 = \tan^{-1}\frac{\sin (\pi x/s)}{e^{\pi y/s} - \cos (\pi x/s)} \quad (23)$$

$$S_3 = \tan^{-1}\frac{\sin (\pi y/h)}{e^{\pi x/h} - \cos (\pi y/h)} \quad (24)$$

The remaining sum to consider, S_5 of (21), does not converge rapidly for small x and y. But neither does it converge very slowly. Slow convergence is prevented by the m^2 in the denominator of the RHS of (21). For practical purposes (21) yields, as it stands, good enough results, without undue labor. Nevertheless the author has obtained a very rapidly converging series for the RHS of (21). It is not a compact expression and its proof requires several pages. To save space the rapidly converging series is not presented. If one sums the first 100 terms of the RHS of (21) as it stands, the absolute value of the error, committed by omitting the remaining terms, will be less than (see *Whittaker* and *Robinson*, 1944, p. 137, Ex. 2)

$$\left(\sum_{101}^\infty \frac{1}{m^2}\right)\frac{h}{\pi(b-a)}\, e^{-101\pi x/h} = 0.005000\,\frac{h}{\pi(b-a)}\, e^{-101\pi x/h} \quad (24a)$$

and hence negligible even if $x = 0$.

Φ for Figure 2a—Observe that the ratios of hyperbolic terms in (13) may be written

$$\frac{\cosh [m\pi(h-y)/s]}{\sinh (m\pi h/x)} = e^{-m\pi y/s} + \frac{e^{-m\pi h/s}\cosh (m\pi y/s)}{\sinh (m\pi h/s)} \quad (25)$$

$$\frac{\cosh [m\pi(s-x)/h]}{\sinh (m\pi s/h)} = e^{-m\pi x/h} + \frac{e^{-m\pi s/h}\cosh (m\pi x/h)}{\sinh (m\pi s/h)} \quad (26)$$

Now substitute the RHS of (7) and (8) and of (25) and (26) into (13), to obtain, after rearranging (and with new symbols V, T_1, T_2, $\cdots$, defined as below)

$$\frac{\pi}{2}\frac{\Phi - C}{\psi_0} = V(x, y) \tag{26a}$$

where

$$V(x, y) = -T_1 - T_2 + T_3 + T_4 - T_5 - T_6 \tag{27}$$

where further

$$T_1 = \sum_1^\infty \frac{1}{m}\cos\frac{m\pi x}{s}\, e^{-m\pi y/s} \qquad \text{(use (34))} \tag{28}$$

$$T_2 = \sum_1^\infty \frac{1}{m}\cos\frac{m\pi x}{s}\, \frac{e^{-m\pi h/s}\cosh(m\pi y/s)}{\sinh(m\pi h/s)} \tag{29}$$

$$T_3 = \sum_1^\infty \frac{1}{m}\cos\frac{m\pi y}{h}\, e^{-m\pi x/h} \qquad \text{(use (35))} \tag{30}$$

$$T_4 = \sum_1^\infty \frac{1}{m}\cos\frac{m\pi y}{h}\, \frac{e^{-m\pi s/h}\cosh(m\pi x/h)}{\sinh(m\pi s/h)} \tag{31}$$

$$T_5 = \frac{h}{\pi(b-a)}\sum_1^\infty \frac{1}{m^2}\left(\sin\frac{m\pi b}{h} - \sin\frac{m\pi a}{h}\right) \cdot \cos\frac{m\pi y}{h}\, e^{-m\pi x/h} \tag{32}$$

$$T_6 = \frac{h}{\pi(b-a)}\sum_1^\infty \frac{1}{m^2}\left(\sin\frac{m\pi b}{h} - \sin\frac{m\pi a}{h}\right) \cdot \cos\frac{m\pi y}{h}\, \frac{e^{-m\pi s/h}\cosh(m\pi x/h)}{\sinh(m\pi s/h)} \tag{33}$$

Comparing (1) and (2) and remembering that ϕ in (2) is a length, observe that Φ and ψ_0 in the LHS of (27) both have the same dimensions, making (as in (15)) the LHS and RHS of (27) dimensionless.

In (28) to (33) the sums T_1 and T_3 are very slowly convergent for small x and y but this does not matter because (see the Appendix, Eq. (97) instead of (28) and (30) we may use

$$T_1 = -\tfrac{1}{2}\ln\left[2e^{-\pi y/s}\left(\cosh\frac{\pi y}{s} - \cos\frac{\pi x}{s}\right)\right] \tag{34}$$

$$T_3 = -\tfrac{1}{2}\ln\left[2e^{-\pi x/h}\left(\cosh\frac{\pi x}{h} - \cos\frac{\pi y}{h}\right)\right] \tag{35}$$

The other sums in (28) to (33) converge rapidly, or at least rapidly enough for our purposes. A rapidly converging, but not very simple series for T_5 may be obtained from the author on request. The absolute value of the error committed by dropping terms beyond the one-hundredth in the RHS of (32) will be less than the RHS of (24a).

ψ and Φ for Figure 2b—The results so far obtained for ψ and Φ are for the general case of Figure 2a. We now obtain expressions for Figures 2b, 2c, $\cdots$, 2g. For Figure 2b, put $a = 0$ and $b = d$ in (16) and (27) and auxiliary equations. The equations will remain unchanged except (21) and (22), and (32) and (33), which become (we use a superscript notation from here on to distinguish special cases; for example the superscript b in the next six equations refers to the problem of Figure 2b)

$$S_5^b = \frac{h}{\pi d}\sum_1^\infty \frac{1}{m^2}\sin\frac{m\pi d}{h}\sin\frac{m\pi y}{h}\, e^{-m\pi x/h} \tag{36}$$

$$S_6^b = \frac{h}{\pi d}\sum_1^\infty \frac{1}{m^2}\sin\frac{m\pi d}{h}\sin\frac{m\pi y}{h} \cdot \frac{e^{-m\pi s/h}\sinh(m\pi x/h)}{\sinh(m\pi s/h)} \tag{37}$$

$$T_5^b = \frac{h}{\pi d}\sum_1^\infty \frac{1}{m^2}\sin\frac{m\pi d}{h}\cos\frac{m\pi y}{h}\, e^{-m\pi x/h} \tag{38}$$

$$T_6^b = \frac{h}{\pi d}\sum_1^\infty \frac{1}{m^2}\sin\frac{m\pi d}{h}\cos\frac{m\pi y}{h} \cdot \frac{e^{-m\pi s/h}\cosh(m\pi x/h)}{\sinh(m\pi s/h)} \tag{39}$$

Therefore (16) becomes

$$\frac{\pi}{2}\frac{\psi_0 - \psi^b}{\psi_0} = S_1 - S_2 + S_3 - S_4 - S_5^b + S_6^b \tag{40}$$

and (26a) and (27) become

$$V^b(x, y) = \frac{\pi}{2}\frac{\Phi - C^b}{\psi_0} = -T_1 - T_2 + T_3 + T_4 - T_5^b - T_6^b \tag{41}$$

ψ and Φ for Figure 2c—Put $d = h$ in (36) to (39) and obtain, since $\sin m\pi = 0$

$$S_5^c = 0, \quad S_6^c = 0, \quad T_5^c = 0, \quad T_6^c = 0 \tag{42}$$

Therefore (16) and (27) become

$$\frac{\pi}{2}\frac{\psi_0 - \psi^c}{\psi_0} = S_1 - S_2 + S_3 - S_4 \tag{43}$$

$$V^c(x, y) = \frac{\pi}{2}\frac{\Phi^c - C^c}{\psi_0} = -T_1 - T_2 + T_3 + T_4 \tag{44}$$

ψ and Φ for Figure 2d—Let in (21) and (22), $a = 0$, and $b = d$ and then let $d \to 0$, so that (with d dropping out of results as it should)

$$\frac{h}{\pi(b-a)}\frac{1}{m^2}\left(\sin\frac{m\pi b}{h} - \sin\frac{m\pi a}{h}\right) = \frac{h}{\pi d}\frac{1}{m^2}\sin\frac{m\pi d}{h} \to \frac{h}{\pi d}\frac{1}{m^2}\frac{m\pi d}{h} = \frac{1}{m} \tag{45}$$

Therefore, using (45) in (21) and (22) and comparing with (19) and (20), find

$$S_6^d = S_4, \qquad S_5^d = S_3 \tag{46}$$

so that (16) becomes

$$\frac{\pi}{2}\frac{\psi_0 - \psi^d}{\psi_0} = S_1 - S_2 \tag{47}$$

Similarly

$$T_6^d = T_4, \qquad T_5^d = T_3 \tag{48}$$

so that (27) becomes

$$V^d(x, y) = \frac{\pi}{2}\frac{\Phi^d - C^d}{\psi_0} = -T_1 - T_2 \tag{49}$$

ψ and Φ for Figure 2e—Comparing Figures 2a and 2e, put in (21) and (22) $b = h$ and $a = h - g$ and obtain after trigonometric reduction

$$S_5^e = \frac{h}{\pi g}\sum_1^\infty (-1)^m \frac{1}{m^2} \sin\frac{m\pi g}{h} \sin\frac{m\pi y}{h} e^{-m\pi x/h} \tag{50}$$

$$S_6^e = \frac{h}{\pi g}\sum_1^\infty (-1)^m \frac{1}{m^2} \sin\frac{m\pi g}{h} \sin\frac{m\pi y}{h} \cdot \frac{e^{-m\pi s/h}\sinh(m\pi x/h)}{\sinh(m\pi s/h)} \tag{51}$$

Whence (16) becomes

$$\frac{\pi}{2}\frac{\psi_0 - \psi^e}{\psi_0} = S_1 - S_2 + S_3 - S_4 - S_5^e + S_6^e \tag{52}$$

Similarly, we find from (32) and (33)

$$T_5^e = \frac{h}{\pi g}\sum_1^\infty (-1)^m \frac{1}{m^2} \sin\frac{m\pi g}{h} \cos\frac{m\pi y}{h} e^{-m\pi x/h} \tag{53}$$

$$T_6^e = \frac{h}{\pi g}\sum_1^\infty (-1)^m \frac{1}{m^2} \sin\frac{m\pi g}{h} \cos\frac{m\pi y}{h} \cdot \frac{e^{-m\pi s/h}\cosh(m\pi x/h)}{\sinh(m\pi s/h)} \tag{54}$$

and (27) becomes

$$V^e = \frac{\pi}{2}\frac{\Phi^e - C^e}{\psi_0} = -T_1 - T_2 + T_3 + T_4 - T_5^e - T_6^e \tag{55}$$

ψ and Φ for Figure 2f—In (50), (51), (53), and (54), let $g \to 0$ so that $\sin(m\pi g/h) \to m\pi g/h$ and find (with g now dropping out of results as it should)

$$S_5^f = \sum_1^\infty (-1)^m \frac{1}{m} \sin\frac{m\pi y}{h} e^{-m\pi x/h} \qquad \text{(use (62))} \tag{56}$$

$$S_6^f = \sum_1^\infty (-1)^m \frac{1}{m} \sin\frac{m\pi y}{h} \frac{e^{-m\pi s/h}\sinh(m\pi x/h)}{\sinh(m\pi s/h)} \tag{57}$$

$$T_5^f = \sum_1^\infty (-1)^m \frac{1}{m} \cos\frac{m\pi y}{h} e^{-m\pi x/h} \qquad \text{(use (63))} \tag{58}$$

$$T_6^f = \sum_1^\infty (-1)^m \frac{1}{m} \cos\frac{m\pi y}{h} \frac{e^{-m\pi s/h}\cosh(m\pi x/h)}{\sinh(m\pi s/h)} \tag{59}$$

Therefore (16) and (27) become, respectively

$$\frac{\pi}{2}\frac{\psi_0 - \psi^f}{\psi_0} = S_1 - S_2 + S_3 - S_4 - S_5^f + S_6^f \tag{60}$$

$$V^f = \frac{\pi}{2}\frac{\Phi^f - C^f}{\psi_0} = -T_1 - T_2 + T_3 + T_4 - T_5^f - T_6^f \qquad \text{(see (64))} \tag{61}$$

Notice that the sums in (56) and (58) converge very slowly for small x/h. This does not matter since they can be summed analytically (see (98) and (100)) with the results

$$S_5^f = -\tan^{-1}\frac{\sin(\pi y/h)}{e^{-\pi x/h} - \cos(\pi y/h)} + \tan^{-1}\frac{\sin(2\pi y/h)}{e^{-2\pi x/h} - \cos(2\pi y/h)} \tag{62}$$

$$T_5^f = \tfrac{1}{2}\ln\left[2e^{-\pi x/h}\left(\cosh\frac{\pi x}{h} - \cos\frac{\pi y}{h}\right)\right] - \tfrac{1}{2}\ln\left[2e^{-2\pi x/h}\left(\cosh\frac{2\pi x}{h} - \cos\frac{2\pi y}{h}\right)\right] \tag{63}$$

Eq. (63) could be further simplified but it is better, in order to simplify the expression $(T_3 + T_5^f)$ in (61), to leave (63) as it stands. We then find for $(T_3 + T_5^f)$, in view of (36) and (6)

$$T_3 + T_5^f = -\tfrac{1}{2}\left[\ln 2 - \frac{2\pi x}{h} + \ln\left(\cosh\frac{2\pi x}{h} - \cos\frac{2\pi y}{h}\right)\right] \tag{64}$$

ψ and Φ for Figure 2g—For our last case we refer to Figure 2a and denote the semiheight $(b - a)/2$ of the strip by Δ. That is, $b - a = 2\Delta$, $b = c + \Delta$, $a = c - \Delta$. Therefore in (21), (22), (32) and (34) we find upon letting $\Delta \to 0$

$$\frac{h}{\pi(b-a)}\left(\sin\frac{m\pi b}{h} - \sin\frac{m\pi a}{h}\right) = \frac{h}{2\pi\Delta}\left[\sin\frac{m\pi(c+\Delta)}{h} - \sin\frac{m\pi(c-\Delta)}{h}\right] = \frac{h}{2\pi\Delta} 2\sin\frac{m\pi\Delta}{h}\cos\frac{m\pi c}{h} \to m\cos\frac{m\pi c}{h}$$

So that (with Δ dropping out of the analysis, as it should)

$$S_5^g = \sum_1^\infty \frac{1}{m}\cos\frac{m\pi c}{h}\sin\frac{m\pi y}{h} e^{-m\pi x/h} \qquad \text{(see (71))} \tag{65}$$

$$S_6{}^g = \sum_1^\infty \frac{1}{m} \cos \frac{m\pi c}{h} \sin \frac{m\pi y}{h} \frac{e^{-m\pi s/h} \sinh (m\pi x/h)}{\sinh (m\pi s/h)} \qquad (66)$$

$$T_5{}^g = \sum_1^\infty \frac{1}{m} \cos \frac{m\pi c}{h} \cos \frac{m\pi y}{h} e^{-m\pi x/h} \qquad \text{(see (72))} \qquad (67)$$

$$T_6{}^g = \sum_1^\infty \frac{1}{m} \cos \frac{m\pi c}{h} \cos \frac{m\pi y}{h} \frac{e^{-m\pi s/h} \cosh (m\pi x/h)}{\sinh (m\pi s/h)} \qquad (68)$$

Accordingly (16) and (27) become

$$\frac{\pi}{2} \frac{\psi_0 - \psi^g}{\psi_0} = S_1 - S_2 + S_3 - S_4 - S_5{}^g + S_6{}^g \qquad (69)$$

$$V^g(x, y) = \frac{\pi}{2} \frac{\Phi^g - C^g}{\psi_0}$$

$$= -T_1 - T_2 + T_3 + T_4 - T_5{}^g - T_6{}^g \qquad (70)$$

The sums in (65) and (67) converge slowly for small x and y. Therefore for small x and y (see (101) and (102)) use

$$S_5{}^g = \tfrac{1}{2} \tan^{-1} \frac{\sin [\pi(y + c)/h]}{e^{\pi x/h} - \cos [\pi(y + c)/h]} + \tfrac{1}{2} \tan^{-1} \frac{\sin [\pi(y - c)/h]}{e^{\pi x/h} - \cos [\pi(y - c)/h]} \qquad (71)$$

$$T_5{}^g = -\tfrac{1}{4} \ln \left\{ 2e^{-\pi x/h} \left[\cosh \frac{\pi x}{h} - \cos \frac{\pi(y + c)}{h} \right] \right\} - \tfrac{1}{4} \ln \left\{ 2e^{-\pi x/h} \left[\cosh \frac{\pi x}{h} - \cos \frac{\pi(y - c)}{h} \right] \right\} \qquad (72)$$

Notice that putting $c = 0$ in the RHS of (65) yields S_3 of (19). That is $S_5{}^g |_{c=0} = S_3$; or since by the second of (46) we have $S_3 = S_5{}^d$, we find

$$S_5{}^g |_{c=0} = S_5{}^d$$

which, comparing Figures 2d and 2g, is a check on previous work. Similarly $S_6{}^g$, $T_5{}^g$, and $T_6{}^g$ go over to $S_6{}^d$, $T_5{}^d$, and $T_6{}^d$ when $c = 0$, as they should.

Evaluation of the constant C—In considering the constant C the situations for Figures 2b, 2c and 2d and for Figures 2a, 2e, 2f, and 2g are considered separately. For Figures 2b, 2c, and 2d, let $\Phi(x_0, 0)$ be the value of an equipotential surface passing through the point (r, O), and let us identify the equipotential passing through (r, O) with the shape of a drainage facility assumed running full to the level $y = 0$; that is, r is the semi-width of the ditch or tube. Then since it has been agreed (see below (2)) to take the reference level at the x-axis, we see that the left hand equality of (41) becomes

$$\frac{\pi}{2} \frac{O - C^b}{\psi_0} = V^b(r, O)$$

That is

$$C^b = -(2/\pi)\psi_0 V^b(r, O) \qquad (73)$$

where $V^b(r, O)$ is to be obtained from the *RHS* of (41) by putting x and y in the T's respectively equal to r and O. Similarly one obtains from (44) and (49)

$$C^c = -(2/\pi)\psi_0 V^c(r, O) \qquad (74)$$

$$C^d = -(2/\pi)\psi_0 V^d(r, O) \qquad (75)$$

where $V^c(r, O)$ is evaluated from the RHS of (44) and $V^d(r, O)$ from the RHS of (49).

To obtain C for Figures 2a, 2e, 2f, and 2g we observe that the water table stands above the sink at all points, including points immediately over the sink. Therefore we cannot, as before, simultaneously identify a point on the sink with a point on the water table. Instead we must take, in (26), $V(x, y) = V(0, 0)$ when $\Phi = 0$. We obtain then for the cases a, e, f, and g, using a composite notation to show four equations in one

$$C^{aefg} = -(2/\pi)\psi_0 V^{aefg}(0, 0) \qquad (76)$$

where V^a is obtained from (27), (34), (29), (35), (31), (32), and (33); $V^e(0, 0)$ from (44), (34), (29), (35), and (31); $V^f(0, 0)$ from (61), (34), (29), (35), and (31); and $V^g(0, 0)$ from (70), (34), (29), (35), (31), (72), (68), (63), and (59).

In (27), (44), (61), and (70), notice that

$$(-T_1 + T_3)$$

in view of (34) and (35) simplifies to

$$-T_1 + T_3 = \tfrac{1}{2} \ln \frac{e^{-\pi y/s} [\cosh (\pi y/s) - \cos (\pi x/s)]}{e^{-\pi x/h} [\cosh (\pi x/h) - \cos (\pi y/h)]}$$

an expression which when x and y both approach zero reduces, in view of *Dwight* [1947, formulas 415.02, 675.2 where cubed terms are to be neglected] to the form

$$-T_1 + T_3 = \ln \frac{h}{s} + \frac{\pi}{2} \left(\frac{x}{h} - \frac{y}{s} \right), \qquad (x, y \to 0)$$

In particular when x and y are both zero, as for $V(0, 0)$, we have

$$-T_1 + T_3 = \ln \frac{h}{s}, \qquad (x, y = 0)$$

Formulas for the hydraulic head—Using the values of C^{bcd} of (73), (74), and (75) in the equalities at the left of (41), (44), and (49), and using then (1) and (2) we find

$$\phi^{bcd}(x, y) = \frac{2sR}{k} \frac{1}{\pi} [V^{bcd}(x, y) - V^{bcd}(r, O)] \qquad (77)$$

and similarly from (76), and from (26a), where the superscript a on C and V is to be understood), and further from (55), (61), (70), (1), and (2) we find

$$\phi^{aefg}(x, y) = \frac{2sR}{k}\frac{1}{\pi}[V^{aefg}(x, y) - V^{aefg}(0, 0)] \quad (78)$$

The quantity ϕ^{bcd} in (77) gives the hydraulic head in the soil for cases b, c and d of Figure 2; and ϕ^{aefg} for cases $aefg$ of the same figure.

Formulas for the hydraulic head in a submerged drain tube—In the last section we have seen that a drain tube which has the shape of an equipotential enclosing a slit sink in Figures 2a, 2e, 2f, and 2g will not ordinarily intercept the x-axis. Therefore the hydraulic head over such a sink will be negative. In particular, the hydraulic head at all points on a (nearly) circular drain tube of Figure 2g, whose circumference includes a point $(x, y) = (r, c)$, is obtained from expression (78) by changing (x, y) to (r, c) with the result

$$\phi^{g}(r, c) = \frac{2sR}{k}\frac{1}{\pi}[V^{g}(r, c) - V^{g}(0, 0)] \quad (79)$$

Similarly for Figure 2f we find

$$\phi^{f}(r, h) = \frac{2sR}{k}\frac{1}{\pi}[V^{f}(r, h) - V^{f}(0, 0)] \quad (80)$$

We point out (an important matter in applying (79) and (80)) that unless in (79) the value of r is such that $\phi = -c$, the drain tube will have to be under suction or pressure in order for the theoretical conditions to be realized and hence for (79) to be valid. A similar statement holds for (80). To keep this paper within bounds, (79) and (80) will not be further discussed.

Height of water table—Put $y = 0$ in (77) to obtain the height $\phi^{bcd}(x, 0)$ ($= z$ of Figures 2b, c, d) of the water table above the reference level. The result is

$$\phi^{bcd}(x, 0) = \frac{2sR}{k}\frac{1}{\pi}[V^{bcd}(x, 0) - V^{bcd}(r, 0)] \quad (81)$$

Similarly from (78)

$$\phi^{aefg}(x, 0) = \frac{2sR}{k}\frac{1}{\pi}[V^{aefg}(x, 0) - V^{aefg}(0, 0)] \quad (82)$$

Putting $x = s$ in (81) and (82) gives for their left-hand sides the height H of the cases in Figure 2.

Case d is of particular interest. For it we have from (81) (with z^d used for $\phi^d(x, 0)$)

$$z^d = \frac{2sR}{k}\frac{1}{\pi}[V^d(x, 0) - V^d(r, 0)] \quad (83)$$

or in elemental terms, using (49), (34), and (29) with (83) and simplifying with the aid of *Dwight* [1947, formula 403.4]

$$z^d = \frac{2sR}{k}\frac{1}{\pi}\left[\ln\frac{\sin(\pi x/2s)}{\sin(\pi r/2s)} + \sum_{m=1}^{\infty}\frac{1}{m}\left(\cos\frac{m\pi r}{s} - \cos\frac{m\pi x}{s}\right)\frac{e^{-m\pi h/s}}{\sinh(m\pi h/s)}\right] \quad (84)$$

where in numerical computations one should use, to save work, the identity

$$e^{-m\pi h/s}/\sinh(m\pi h/s) = \coth(m\pi h/s) - 1 \quad (85)$$

(Another useful computational hint for (84) is to obtain natural logarithms by reading a table of exponential values inversely. ***Holtappel's*** [1938] tables are especially valuable for practical work, as they can be read inversely to give ln x to three or four significant figures without interpolation. Thus $\ln 22.07 = 3.094$ from ***Holtappel***, [*p.* 21].)

The maximum height H of the water table is obtained by putting $x = s$ in (84). The result is, utilizing (85) and noting for practical work that $\sin(\frac{1}{2}\pi r/s) = \frac{1}{2}\pi r/s$

$$H^d = \frac{2sR}{k}\frac{1}{\pi}\left[\ln\frac{2s}{\pi r} + \sum_{m=1}^{\infty}\frac{1}{m} \cdot \left(\cos\frac{m\pi r}{s} - \cos m\pi\right)\left(\coth\frac{m\pi h}{s} - 1\right)\right] \quad (86)$$

From (86) we see that the maximum water-table height is directly proportional to R/k, the ratio of rainfall to soil hydraulic conductivity. Thus doubling the rainfall rate doubles the water table height. The same statement holds for Figures 2b and 2c. In (86) we see that H^d is not directly proportional to $2s$ because $2s$ is involved in the logarithm term, and in the sum terms, as well as being a factor of the whole right-hand side.

If in (86), $h/s \to \infty$; that is, if the impermeable layer is at great depth, with s staying finite, then (86) reduces to the very simple result

$$H^d \text{ (for } h/s \to \infty) = (2sR/k)(1/\pi)\ln(2s/\pi r) \quad (87)$$

which is independent of the (great) depth h, as it should be. Since in (87), $\ln(2s/\pi r)$ varies very slowly compared to s, we can say, for practical purposes, that for the case of Figure 2d doubling the tile spacing will double the height H in the figure of the water table for the same rainfall. This statement is true if the soil is of uniform hydraulic conductivity to great depth and if no drainage water seeps away at the great depth.

In (86) let F be defined by

$$F = \frac{1}{\pi}\left[\ln\frac{2s}{\pi r} + \sum_{m=1}^{\infty}\frac{1}{m} \cdot \left(\cos\frac{m\pi r}{s} - \cos m\pi\right)\left(\coth\frac{m\pi h}{s} - 1\right)\right] \quad (88)$$

Then (86) becomes

$$H^d = (2sR/k)F(2r/2s,\, h/2s) \quad (89)$$

where we have shown F as a function of $2r/2s$ and $h/2s$ rather than of say r/s and s/h because the ratios $2r/2s$ and $h/2s$ are convenient in practice. To facilitate computation of H^d, a table of F has been prepared and is given as Table 1.

We see from the table, for example, that if $2s = 100$ ft and $h = 4$ ft, so that $h/2s = 0.04$; and if $2r = \frac{1}{2}$ ft, so that $2r/2s = 0.005$, the value of H will be $H = (100R/k)$ (3.643). Accordingly, if the rainfall rate is $\frac{1}{2}$ in/day and the hydraulic conductivity 96 in/day, we find $H = 1.90$ ft.

Fall of the water table when rain ceases—At the instant rainfall ceases the rate of fall of the water table can be computed, since this rate will be the vertical velocity ('velocity' in the Darcy law sense) computed at $y = 0$ divided by the fraction p of drainable pore space. Since the vertical velocity at any point in the soil is

$$-k\partial\phi/\partial y = -\partial\Phi/\partial y$$

the rate of fall G midway between drain tubes ($x = s$) is

$$G = -(1/p)[\partial\Phi/\partial y]_{x=s,\,y=0} \quad (90)$$

where Φ is as in (13). The formula (90) can only be used at the instant rainfall ceases, because after that instant the potential distribution will have changed and will continue to change until flow ceases. Evaluation of the RHS of (90) yields, as it physically should, the result R/p; this is the same result found when the subscript $x = s$ is changed to $x = x$ in the equation.

FLOW NETS

Three flow nets (Fig. 3) corresponding to Figures 2bcd have been calculated. Eq. (40), (43), and (47) were used for the streamlines and (77) for the lines of equal hydraulic head or equipotentials. The net function in each case is expressed in per cent.

In each net the lowest point of the water table is taken to be four feet below the soil surface and the impervious layer is at a 14-ft depth. Therefore the theoretical flow region is of height $h = 10$ ft for all three nets. The semispacing s for all three nets is 50 ft to yield a realistic drain spacing $2s = 100$ ft. A value of R/k was chosen ($= 0.01087$) to make $H = 2.000$ ft in the d part of Figure 3. For Figures 3b and 3c the values of H for this value of R/k turned out to be 1.874 ft and 1.330 ft.

TABLE 1 – *Values of $F(2r/2s, h/2s)$ of (88) and (89) for computing the maximum height H ($= H^d$) of the water table for Figure 2d, with R the rainfall rate and k the hydraulic conductivity (R and k in the same units, say inches per day); multiply the entries by $2sR/k$ to obtain the height H, in the units used for s*

$\frac{h}{2s}$	$2r/2s$				
	0.0025	0.005	0.01	0.02	0.04
0.01	12.79	12.57	12.33	12.03	11.52
0.02	6.761	6.541	6.318	6.077	5.771
0.04	3.864	3.643	3.421	3.195	2.954
0.08	2.522	2.301	2.080	1.858	1.633
0.16	1.961	1.741	1.520	1.299	1.077
0.32	1.787	1.566	1.345	1.125	0.9040
0.64	1.764	1.543	1.323	1.102	0.8811
1.00	1.763	1.543	1.322	1.101	0.8808
∞	1.763	1.543	1.322	1.101	0.8808

In Figure 3b the equipotential passing through the point $x = r = (1/20)h = 0.5$ ft and $y = 0$ was identified with the ditch (at potential zero) so that the semi-width of the ditch in Figure 3b is 0.5 ft. The slit depth d was taken to be one foot. Therefore the depth of the ditch is somewhat greater than one foot (1.04 ft). The zero equipotential approximates closely the shape of a ditch one might find in practice.

In Figure 3c the equipotential passing through the point $x = (1/20)h = 0.5$ ft and $y = 0$ was also identified with the ditch. But here the theoretical ditch does not look like a real one. Its walls slope in the wrong direction. Nevertheless it is clear from physical intuition, and more specifically from the small changes in the values of the three computed negative equipotentials shown in the lower left of the net, that changing the slope of the walls of the ditch to make its shape approximate the shape of a real ditch would only influence the flow net slightly. Therefore the flow net of Figure 3c may be taken to represent the flow net for drainage by a real ditch, flowing with water in it to the level of the water table, $y = 0$, and penetrating down to an impermeable layer, $y = h$.

In Figure 3d the equipotential passing through the point $(x, y) = (r, y) = (0.05h, 0)$ was again chosen to be the zero equipotential and verifies that the zero equipotential, as was indicated in Figure 2d, is a semicircle. In fact the equipoten-

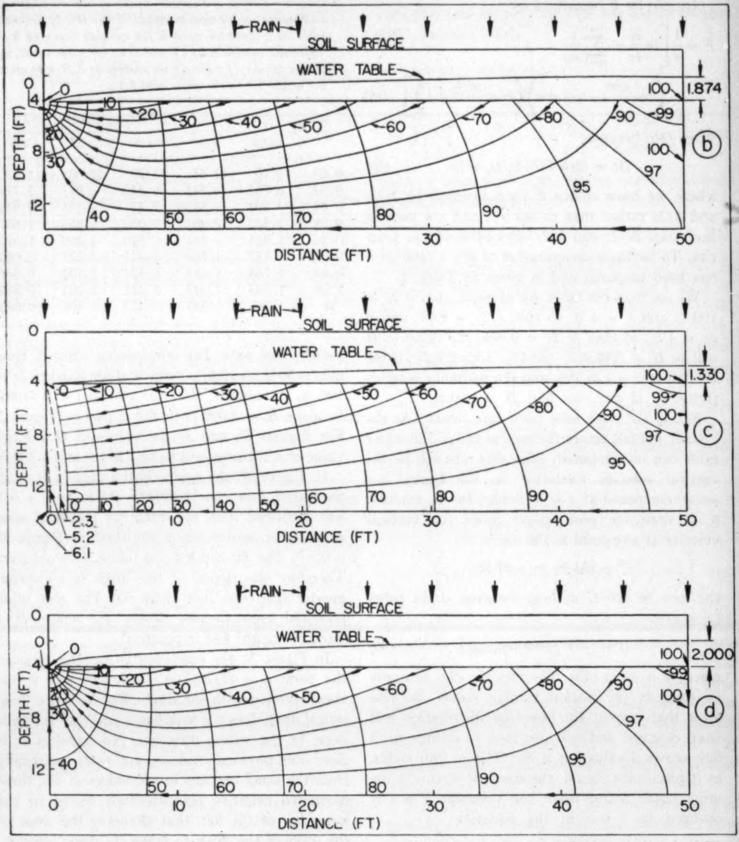
RAIN
SOIL SURFACE
WATER TABLE
DEPTH (FT)
DISTANCE (FT)
0
4
8
12
0
10
20
30
40
50
60
70
80
90
95
97
99
100
1.874
b
0
4
8
12
0
10
20
30
40
50
60
70
80
90
95
97
99
100
1.330
-2.3
-5.2
-6.1
c
0
4
8
12
0
10
20
30
40
50
60
70
80
90
95
97
99
100
2.000
d

Fig. 3 – Flow nets b, c, and d corresponding to cases b, c, and d of Figure 2 when a full-flowing ditch or half-filled drain tube is identified with a surface of equal hydraulic head surrounding a slit or line sink; the water table heights shown are for a rainfall-hydraulic conductivity ratio $R/k = 0.01087$ for each net

tials for some distance away from the drain center are semicircles, or nearly so, as they should be.

Above each of the flow nets are shown curves of the variation with distance from the drains of the height of the water table, corresponding respectively to the maximum heights 2.000, 1.874 and 1.330 ft. Since the ratio $R/k = 0.01087$ to produce these heights is approximately 0.01 one may interpret the water tables to correspond to an average rainfall of about 0.1 inches per day for a soil of hydraulic conductivity $k = 10$ in/day. When it is remembered that the depths of the drains for Figures 3d, 3b and 3c are, respectively, 0.5 ft, 1.04 ft, and 10 ft, it becomes clear that the corresponding maximum water table heights, 2 ft, 1.874 ft, and 1.330 ft are not sensitive to the shape of the drain. This statement is true only if each drain has water standing in it to the level $y = 0$.

From (81) (with $x = s$ and $r = 0.05h$) it is seen that the equipotentials of Figures 3b, 3c, and 3d have involved the computation of the differences $V^b(s, 0) - V^b(0.05h, 0)$ etc to correspond to equipotential differences of 100 pct. To relate the values of the equipotentials, as given in percentages on the nets, to the basic computed numbers, which were obtained with considerable labor, the following computed values (with $s = 50$ and $h = 10$) are given: $V^b(50, 0) = 1.4137$; $V^b(0.5, 0) = -4.0018$; $V^c(50, 0) = 1.4137$ (the same value to four decimals as $V^b(50, 0)$); $V^c(0.5, 0) = -2.4300$; $V^d(50, 0) = 1.414$; $V^d(0.5, 0) = -4.364$. For Figure 3b, the difference in potential, 100 percent, corresponds therefore to $[1.4137 - (-4.0018)] = 5.4155$; for Figure 3c, 3.8437; and for Figure 3d, 5.778. The numbers 5.778, 5.4155 and 3.8437 are in direct proportion to the previously given water table heights, 2 ft, 1.874 ft, and 1.330 ft, respectively.

THE THEORY COMPARED WITH FIELD DATA

Kirkham and De Zeeuw [1952] have obtained, in replicated field experiments, and under average steady rainfall conditions, water-table shapes for 8- and 16-meter spacing of tube (tile) drains; and maximum heights of water tables for 8-, 10-, 12-, and 16-meter spacings, both for tile and ditch drains. We may compare the theory with their results. In the following the numbers in parentheses refer to the page number in the [1952] reference. The drain tiles were of 7 cm outside diameter (p. 286), with their measured centers averaging 93.5 cm (p. 287) below the soil surface. The tiles were installed on a trench bottom of average measured depth 97 cm (p. 287). The trench bottom when made was nominally 14 cm wide (p. 286) and when the tiles were in place the trench was back-filled to a height 15 cm above the trench bottom with a highly permeable material fabricated from oligotrophic peat (p. 292). Thus, the tile lines likely behaved as if they were of greater outside diameter than 7 cm. We take the diameter to be 9 cm, a figure which need not be exact because we have seen by (84) and (86) (compare also Fig. 3) that tube diameter enters in the theory logarithmically and hence changes in tile diameter will not influence results greatly. But it would be wrong to take the tile diameter equal to the width, 14 cm, of the porous peat backfill, even if the porous peat were infinitely permeable, because the peat was not placed beneath the tile.

An impermeable layer was at 180 cm depth (p. 287) and the average hydraulic conductivity of the soil in the flow region (see their Fig. 4) was about 50 to 150 mm/day, varying with depth. The rainfall averaged 2.82 mm/day (p. 290) for the 13-day test period, Nov. 27 to Dec. 9, 1950 (p. 290). Evapotranspiration averaged 0.40 mm per day from Nov. 24 to Dec. 14 (p. 293) and we assume the same value 0.40 mm for the test period Nov. 27 to Dec. 9. Test wells for measuring water-table height were located (p. 287) at positions 0.18, 1, 2, and 4 meters from the tile centers for the 8-meter spacing of tiles. The water-table distance below the soil surface at these positions averaged (see their Fig. 7), respectively, 84.9, 74.1, 65.9, and 60.4 cm. For the 16-meter spacing the test wells (p. 287) were 0.18, 1, 2, 4, and 8 meters from the tile centers, and the water-table distance below the soil surface at these respective wells averaged 82.4, 62.7, 48.3, 28.1, and 15.5 cm. The depth of the water table midway between 8-, 10-, 12-, and 16-meter spaced tile drains was (see their Fig. 6), respectively, 60.4, 48.3, 28.1, and 15.5 cm. The depth of the water table midway between 8-, 10-, 12-, and 16-meter spaced tile drains was (see again their Fig. 6), respectively, 60.4, 47.3, 37.2, and 15.5 cm. Corresponding figures for the (same spaced) ditch drains are 39.9, 35.0, 26.2, and 7.7 cm. The ditches were of trapezoidal shape (p. 286), nominally 60 cm deep, 25 cm wide at the bottom, and 115 cm wide at the top. The ditches were full of water (p. 290) to 50 cm depth and because of uncleanness we assume them to have been 55 cm deep. We further assume, in order to use the theoretically simple cases of Figure 2d, that the ditch bottoms were of effectively semicircular cross section with centers 50 cm from the soil surface and radii 9 cm. We have seen in Figure 3 that heights of water tables are not very sensitive to shapes of the ditches. By subtracting the tile center depth from the water table depths, etc., we have made a table of values (Table 2) from the above data to test the theory (Figures 4A and 4B).

In Figure 4A, which is for tile drains, the theoretical curve is obtained from the right-hand side of (84) utilizing the experimental values $R = 2.42$ mm per day, $k = 100$ mm per day, $2s = 8$ meters, $r = 4.5$ cm and $h = 86$ cm. The data fit the curve unexpectedly well.

TABLE 2 – *Data of field drainage experiments of Kirkham and DeZeeuw [1952] tabulated in notation of Figure 2d of present paper*

Drain type[a]	Spacing (2s)	x	z	H
	m	m	cm	cm
Tile drains with r = 4.5 cm and h = 86 cm	8	0.18	8.6	33.1
	8	1.0	19.4	33.1
	8	2.0	27.6	33.1
	8	4.0	33.1	33.1
	10			46.2
	12			56.3
	16	0.18	11.1	78.0
	16	1.00	30.8	78.0
	16	2.00	45.2	78.0
	16	4.00	65.4	78.0
	16	8.00	78.0	78.0
Ditch drains[b] with r = 9 cm and h = 86 cm	8			10.1
	10			15.0
	12			23.8
	16			42.3

[a] For both tile and ditch drain plots, the net precipitation R (rainfall less evapotranspiration) was $R = 2.82 - 0.40 = 2.42$ mm/day; and the hydraulic conductivity of the soil varied from k = 50 mm/day to about k = 150 mm/day [see *Kirkham* and *DeZeeuw*, 1952, Fig. 5].

[b] The ditches are assumed to have an equivalent semicircular bottom of radius 9 cm; see text.

In Figure 4B, which is for open ditches, notice that the ratio R/k is taken as 0.0121, just half the value for Figure 4A. The use of a lower value of R/k here is probably justifiable for two reasons. In the first place, of the 2.42 mm per day of precipitation, some of it must have run off into the ditches making the effective R in R/k less than 2.42 mm per day. Secondly, the data of Kirkham and De Zeeuw show that the hydraulic conductivity is higher for the ditch drainage case than for tile drains, making R/k smaller, since the ditches are located higher in the soil where hydraulic conductivity values up to 200 mm per day were sometimes measured (see their Fig. 5) That a value of R/k occurs for the ditches which is just half that for the drains must be considered as fortuitous. Theory and experiment agree fairly well in Figure 4B.

Comparisons with the theory for z versus x values for the 16-meter drain data of Table 2 are not made since the ratio H/h = 78.0/86 is too large for the theory to be expected to hold. The theory is strictly accurate only as H/h approaches zero. Also, because H/h is not small, a theoretical graph of the relation of H to 2s for the 8- to 16-meter spacing of tiles is not presented. Some calculations have, however, been made. They show that the theory fits the experimental points increasingly poorly as H/h increases from the experimental values 33.1/86 to 78.0/86. In fact, corresponding to 2s = 8, 10, 12, and 16 meters, the theory yields (for k = 100 mm per day and R = 2.42 mm per day as for Figure 4a) the values 33.6, 49.5, 67.3, and 112.3 whereas the corresponding experimental values shown in Table 2 are 33.1, 46.2, 56.3, and 78.0 cm. Only the experimental values 33.1 and 46.2 compare well with the theoretical ones 33.6 and 49.5.

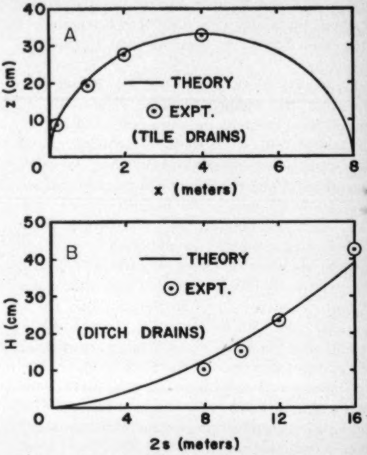

FIG. 4 – Comparison of theory, for the case of Figure 2d (see it for symbols) with experimental field data of *Kirkham* and *De Zeeuw* [1952]; (A) height of water table z versus distance x from tiles, when r = 4.5 cm, h = 86 cm and R/k = 0.0242; (B) midpoint height H of water table versus spacing 2s of semicircular ditches when r = 9 cm, h = 130 cm and R/k = 0.0121; R is rainfall rate; k is soil hydraulic conductivity

It is to be noticed that the experimental data which are compared here with the theory are actual field data, not laboratory model data.

DERIVATION OF DUPUIT-FORCHHEIMER (DF) THEORY

Although *Muskat* [1946, esp. p. 361] has pointed out "the inconsistencies of the Dupuit assumptions with the direct implications of Darcy's law," nevertheless Forchheimer and others have used the theory extensively in application to practical seepage problems. A particularly disturbing implication of the DF theory is that it does not provide for convergence of flow in the vertical direction and hence the shape and size of horizontal tiles and ditches into which the water seeps do not enter into the theory at all. Because of the above matters it was a surprise to discover that the present theory reduces, under special conditions, to DF theory and that accordingly the DF theory is justified for these special conditions, as will be seen.

To derive the DF theory from our theory we refer to (86) and state the special conditions, which are that $r/s \to 0$, that $h/s \to 0$ and that the water table approaches flatness. That is, we will show that (86) goes over to DF theory, provided s is very large compared to r and h in Figure 2d and if the water table approaches flatness.

Let us first consider the sum in (86). In the first place we notice that since the sum converges we can obtain any desired degree of accuracy by summing only for $m = 1, 2, 3, \ldots, M$ where M is finite. Now let us assume that r/s and h/s are sufficiently small, that $\cos (m\pi r/s) \to 1$, and in view of *Dwight* [1947, formula 676.6], that $[\coth (m\pi h/s - 1] \to [s/(m\pi h) - 1] \to s/(m\pi h)$. Then the sum $\sum_1^\infty$ in (86) becomes, if M is taken large enough,

$$\sum_1^\infty \to \sum_1^M \frac{1}{m} (1 - \cos m\pi) \frac{s}{m\pi h} \qquad (m = 1, 2, 3, \cdots)$$

$$= \frac{2s}{\pi h} \sum_1^M \frac{1}{m^2} \to \frac{2s}{\pi h} \sum_1^\infty \frac{1}{m^2} \qquad (m = 1, 3, 5, \cdots)$$

$$= \frac{2s}{\pi h} \frac{\pi^2}{8} = \frac{\pi s}{4h}$$

where we have utilized *Dwight* [1947, formula 48.4].

Formula (86) now becomes, approximately, after the dropping of the superscript d

$$H = \frac{2sR}{k} \frac{1}{\pi} \left[\ln \frac{2s}{\pi r} + \frac{\pi s}{4h} \right] \to \frac{2sR}{k} \frac{1}{\pi} \frac{\pi s}{4h}$$

provided $s \to \infty$ and other quantities stay finite. That is, we have finally when $s \to \infty$

$$H = \frac{2sR}{k} \frac{s}{4h}, \qquad (s \to \infty) \tag{91}$$

which is independent of the drain size and is, as we shall see, nothing but the DF result for Figure 2d if $H \to 0$.

Since (91) is independent of drain size and hence also of drain shape, we can assume that the drain is a ditch drain of depth h to the impervious layer. (But remember that the ditch to be compatible with the preceding work must have water standing in it to a height h.) Now in (91) let Q_1 be the flow entering a drain from one side and let $H_0 = H + h$. Then (91) may be written in the form

$$s = 2kh(H_0 - h)/Q_1 \tag{92}$$

Now if h is the height of water in a ditch or drain, and if H_0 is the height of the water table midway between drains (h and H_0 both being heights above the impermeable layer) and if s is the semispacing of drains, the conventional DF theory yields (see for example *Van Schilfgaarde* and others [1956])

$$s = k(H_0^2 - h^2)/Q_1 \tag{93}$$

To show that (92) and (93) are equivalent when the water table approaches flatness we write (93) as

$$s = k(H_0 + h)(H_0 - h)/Q_1 \tag{94}$$

or since $(H_0 + h) \to 2h$ when the water table approaches flatness, we see that (94) becomes

$$s = 2kh(H_0 - h_0)/Q_1 \tag{95}$$

which is precisely (92).

Since (92) was derived by rigorous methods and is exact insofar as the water table approaches flatness and $s \to \infty$ (with h and r being finite) then (95), the DF theory, is also exact if $s \to \infty$ and the water table approaches flatness. In other words, a rational basis for the DF theory has been obtained. Notice that as the water table approaches flatness there can be no surface of seepage, so (92)–(95) do not involve the complication of surfaces of seepage.

Although DF theory implies when $h/s \to 0$ that drain size makes no difference in H, notice in Table 1, row 1, that with $h/2s$ as small as 0.01 (for example, $h = 4$ ft, $2s = 400$ ft) the radius of the drain still makes an appreciable difference in F and hence in H of (86) or (89). In fact, for $2r/2s = 0.0025$ and 0.04 we find from Table 1 and (89), using obvious notation

$$H_{0.0025}/H_{0.04} = 12.79/11.52 = 1.11$$

or a height difference of 11 percent due to the drain size difference. If $h/2s$ were increased from 0.01 to 0.04 the corresponding result would be,

$$H'_{0.0025}/H'_{0.04} = 3.864/2.954 = 1.31$$

or a height difference of 31 percent due to the drain size difference. Thus for most practical situations use of DF theory will result in an appreciable error.

CONCLUSIONS

Use of exact mathematical methods, together with a justified simplifying physical assumption, have enabled the derivation of formulas for (a) flow nets, (b) the maximum height of the water table, (c) the variation of the water-table height with distance from a drain, and (d) rate of fall of the water-table at the instant rainfall ceases, for seven different cases of tube and ditch drains, when steady rainfall seeps at a steady rate through homogeneous soil to the drains. Water-table heights computed by the formulas agree with water table heights found in field experiments. The theory yields the Dupuit-Forchheimer (DF) theory for the special case that the water table is nearly flat and that the drain spacing is very large compared to a depth of an impermeable layer on which the water-saturated soil rests. Thus a rational basis for DF theory is provided. In practice DF theory should not be used unless the very special conditions for which it becomes valid are realized.

APPENDIX I—PROOF OF CERTAIN FORMULAS

In the proofs below we have assumed, without proof, that the mathematical procedures used would work. For example we have used formulas for functions of real variables, as if the formulas also hold for complex variables, without so proving. That our procedures have been valid has always been checked by numerical tests of the end results. We have not specified in all cases the range of validity of the formulas. Numerical calculations (and analysis not given here) show that the formulas are valid at least for the range of variables in our problem.

In all the summations below it is to be understood that the index of summation is m and that m is to have the value $m = 1, 2, 3, \ldots, \infty$.

Proof of (23) *and* (24)—We need only prove (23), since (24) may be written down by inspection of (17), (19), and (23).

To prove (23) we compare it with (17) and, letting $A = \pi x/s$ and $B = \pi y/s$, we see that our task is: Prove

$$S_1 = \sum \frac{\sin mA e^{-mB}}{m} = \tan^{-1} \frac{\sin A}{e^B - \cos A} \qquad (96)$$

Proof—Substitute the exponential form for the sine [*Dwight*, 1947, formula 408.01] into the first equality in (1), rearrange, and find

$$S_1 = \frac{1}{2i} \sum \frac{e^{m(Ai-B)}}{m} - \frac{1}{2i} \sum \frac{e^{-m(Ai+B)}}{m} \quad ,$$

Next, expand the sums and, utilizing Dwight 601.1, with Dwight's x first equal our $e^{(Ai-B)}$ and then equal our $e^{-(Ai+B)}$ find

$$S_1 = -\frac{1}{2i} \ln \frac{1 - e^{Ai-B}}{1 - e^{-(Ai+B)}} = -\frac{1}{2i} \ln \frac{e^B - e^{Ai}}{e^B - e^{-Ai}}$$

Now use Dwight 408.04 to find

$$S_1 = -\frac{1}{2i} \ln \frac{(e^B - \cos A) - i \sin A}{(e^B - \cos A) + i \sin A}$$

Now represent the numerator of the argument of the logarithm by the vector $Re^{i\theta}$ where R is the magnitude of the vector and θ the angle the vector makes with the real axis. Then

$$e^B - \cos A - i \sin A = Re^{i\theta}$$

where we must have

$$R = [(e^B - \cos A)^2 + \sin^2 A]^{\frac{1}{2}}$$

and

$$\tan \theta = -\sin A/(e^B - \cos A)$$

Similarly we may denote the denominator of the argument of the logarithm by $R'e^{i\theta'}$ where we find

$$R' = R \text{ and } \theta' = -\theta$$

Accordingly

$$S_1 = -\frac{1}{2i} \ln \frac{Re^{i\theta}}{Re^{-i\theta}} = -\frac{1}{2i} \ln e^{2i\theta}$$

or

$$S_1 = -\frac{1}{2i} (2i\theta) = -\theta$$

That is, finally

$$S_1 = \tan^{-1} [\sin A/(e^B - \cos A)]$$

and (96) is proved.

Expression (96) is valid at least for $0 \leqq A \leqq 2\pi$ if B > 0; and is valid for $0 < \mathrm{A} < 2\pi$ if B $= 0$.

Proof of (34) *and* (35)—We need only prove (34), since (35) follows from (29) by inspection of (28) and (34). To prove (34) we compare it with (28); letting $A = \pi x/s$, $B = \pi y/s$, we see that our task is: Prove

$$T_1 = \sum \frac{1}{m} \cos mA e^{-mB}$$
$$= -\tfrac{1}{2} \ln [2e^{-B} (\cosh B - \cos A)] \qquad (97)$$

Proof—Using Dwight 408.02 in the first of (97), find

$$T_1 = \tfrac{1}{2} \sum \frac{e^{m(Ai-B)}}{m} + \tfrac{1}{2} \sum \frac{e^{-m(Ai+B)}}{m}$$

So that by Dwight 601.1

$$T_1 = -\tfrac{1}{2}\ln\left(1 - e^{Ai-B}\right) - \tfrac{1}{2}\ln\left(1 - e^{-(Ai+B)}\right)$$

$$= -\tfrac{1}{2}\ln\left[e^{-B}\left(e^{B} + e^{-B} - e^{Ai} - e^{-Ai}\right)\right]$$

or by Dwight 654.2 and 408.02

$$T_1 = -\tfrac{1}{2}\ln\left[2e^{-B}(\cosh B - \cos A)\right]$$

which is (97), and completes the proof.

Proof of (62) and (63)—To prove (62) we see from (56) and (62), that if we let $\pi y/h = \alpha$ and $\pi x/h = \beta$, our task becomes: Prove that

$$S_b^f = \sum (-1)^m \frac{1}{m}\sin m\alpha e^{-m\beta}$$

$$= -\tan^{-1}\frac{\sin\alpha}{e^{-\beta} - \cos\alpha} + \tan^{-1}\frac{\sin 2\alpha}{e^{-2\beta} - \cos 2\beta} \qquad (98)$$

It is first left to the reader to demonstrate (by expanding and then regrouping terms) that if

$$f(m) = \sin m\alpha e^{-m\beta}$$

then

$$\sum (-1)^m \frac{f(m)}{m} = -\sum\frac{f(m)}{m} + \sum\frac{f(2m)}{m} \qquad (99)$$

The sums on the right are known from (96); whence (98) follows immediately, which was to be proved.

To prove (63) it must be proved that the RHS of (58) is equal to the RHS of (63). Let $A' = \pi y/h$ and $B' = \pi x/h$. Then we must prove that

$$\sum (-1)^m \frac{1}{m}\cos mA' e^{-mB'}$$

$$= \tfrac{1}{2}\ln\left[2e^{-B'}(\cosh B' - \cos A')\right]$$

$$- \tfrac{1}{2}\ln\left[2e^{-2B'}(\cosh 2B' - \cos 2A')\right] \qquad (100)$$

Proof—First observe that (99) is valid if $f(m) = \cos mA'\, e^{-mB'}$. Then use (97) to find that (100) follows immediately.

Proof of (71) and (72)—We first consider (71). Upon comparing (65) and (71) one sees, with $\alpha = \pi y/h$ and $\beta = \pi x/h$, $\gamma = \pi c/h$, that our task is: Prove

$$S_b^g = \sum\frac{1}{m}\cos m\gamma \sin m\alpha e^{-m\beta}$$

$$= \tfrac{1}{2}\tan^{-1}\frac{\sin(\alpha+\gamma)}{e^{\beta} - \cos(\alpha+\gamma)}$$

$$+ \tfrac{1}{2}\tan^{-1}\frac{\sin(\alpha-\gamma)}{e^{\beta} - \cos(\alpha-\gamma)} \qquad (101)$$

Proof—By Dwight 401.05

$$\sin m\alpha \cos m\gamma = \tfrac{1}{2}[\sin m(\alpha+\gamma) + \sin m(\alpha-\gamma)]$$

So that

$$S_b^g = \tfrac{1}{2}\sum\frac{1}{m}\sin m(\alpha+\gamma)e^{-m\beta}$$

$$+ \tfrac{1}{2}\sum\frac{1}{m}\sin m(\alpha-\gamma)e^{-m\beta}$$

But the sums in S_b^g may be written down by use of (96); whence (101) follows immediately, which was to be proved.

To prove (72), we see comparing (67) and (72), and with α, β, and γ as above, that our task is: Prove

$$T_b^g = \sum\frac{1}{m}\cos m\gamma \cos m\alpha e^{-m\beta}$$

$$= -\tfrac{1}{4}\ln\{2e^{-\beta}[\cosh\beta - \cos(\alpha+\gamma)]\}$$

$$- \tfrac{1}{4}\ln\{2e^{-\beta}[\cosh\beta - \cos(\alpha-\gamma)]\} \qquad (102)$$

Proof—By Dwight 401.06

$$\cos m\alpha \cos m\gamma = \tfrac{1}{2}\cos m(\alpha+\gamma) + \tfrac{1}{2}\cos m(\alpha-\gamma)$$

so that

$$T_b^g = \tfrac{1}{2}\sum\frac{1}{m}\cos m(\alpha+\gamma)e^{-m\beta}$$

$$+ \tfrac{1}{2}\sum\frac{1}{m}\cos m(\alpha-\gamma)e^{-m\beta}$$

The sums on the right may be written down immediately from (97), whence (102) follows immediately, which was to be proved.

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Simultaneous Transfer of Heat and Moisture in Porous Media

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Abstract—Simultaneous differential equations for the transfer of heat and moisture in porous media under the combined influence of gravity and gradients of temperature and moisture content are developed. These equations are a generalization of those derived by *Philip* and *de Vries* [1957]. In particular a consistent distinction is made between changes of moisture content in the liquid and the vapor phase.

The interaction between heat and moisture transfer in steady state heat conduction is discussed in detail using numerical values for two soils, a clay loam and a medium sand. The behavior is found to be dependent on the boundary conditions for moisture transfer, on the direction of the temperature gradient and on the ratio of two moisture diffusivities entering in the analysis.

Introduction—In a recent paper *Philip* and *de Vries* [1957] discussed the movement of liquid water and water vapor in porous media under the influence of gradients of temperature and moisture content. In the final paragraph of that paper they presented equations of simultaneous heat and moisture transfer. The present paper extends this approach.

In particular heat transfer by moisture movement is considered in greater detail. Heat of wetting and transfer of sensible heat are taken into account. Furthermore a consequent distinction is made between changes of moisture content in the liquid and the vapor phase, whereas in the final paragraph of the paper cited it was tacitly assumed that changes of moisture contained in the vapor phase are negligible. This may often be admissable, because the vapor content is usually small in comparison with the liquid content (both expressed as g/cm^3). However, there are also many situations where changes in liquid and vapor content can be of the same order. This will be so in particular where these changes are due to moisture movement under the influence of temperature gradients. A number of implications of the new equations will be discussed using numerical data for a coarse textured and a medium textured soil.

Notation—The notation in the present paper is almost the same as that of the paper cited. The most important difference is that the symbol θ is used here to denote the total moisture content (liquid + vapor), whereas in the previous paper it stood for liquid moisture content. For reasons of economy the subscripts l and v are used to indicate the liquid and vapor phases respectively instead of liq and vap. Hence θ_l and θ_v are the moisture contents in the two phases, and ρ_l and ρ_v are the corresponding densities (ρw and ρ in the previous paper).

The following list contains an explanation of the symbols used and the units in which they are expressed. Numerical values of some constants are also included.

a	volumetric air content, cm^3 of air/cm^3
c_p	specific heat of water vapor at constant pressure, cal g^{-1} °C^{-1}
c_l	specific heat of liquid water, cal g^{-1} °C^{-1}
C	volumetric heat capacity of moist porous medium, cal cm^{-3} °C^{-1}
C_d	volumetric heat capacity of dry porous medium, cal cm^{-3} °C^{-1}
D_{atm}	molecular diffusion coefficient of water vapor in air, cm^2 sec^{-1} ($=4.42 \times 10^{-4}\, T^{2.3}/P$)
D_T	$= D_{Tl} + D_{Tv}$ thermal moisture diffusivity, cm^2 sec^{-1} °C^{-1}
D_{Tl}	$= K\gamma\Psi$ thermal liquid diffusivity, cm^2 sec^{-1} °C^{-1}
D_{Tv}	$= fD_{\mathrm{atm}}\nu\beta h(\nabla T)_a/\rho_l\nabla T$ (with $f = S$ for $\theta_l < \theta_{lk}$, $f = a + a\theta_l/(S - \theta_{lk})$ for $\theta_l > \theta_{lk}$) thermal vapor diffusivity, cm^2 sec^{-1} °C^{-1}
D_θ	$= D_{\theta l} + D_{\theta v}$ isothermal moisture diffusivity, cm^2 sec^{-1}
$D_{\theta l}$	$= K\partial\Psi/\partial\theta_l$ isothermal liquid diffusivity, cm^2 sec^{-1}
$D_{\theta v}$	$= \alpha a D_{\mathrm{atm}}\nu g\rho_v(\partial\Psi/\partial\theta_l)/\rho_l RT$ isothermal vapor diffusivity, cm^2 sec^{-1}
E	rate of evaporation, sec^{-1}
g	acceleration due to gravity, cm sec^{-2} ($=981$)
h	relative humidity
j	mechanical equivalent of heat, erg cal^{-1} ($=4.18 \times 10^7$)

$\mathbf{k}$	unit vector in vertical direction
K	unsaturated hydraulic conductivity, cm sec^{-1}
L	heat of vaporization, cal g^{-1} (=585 at 20°C)
L_0	heat of vaporization at reference temperature T_0, cal g^{-1}
p	partial pressure of water vapor, mm Hg
P	total gas pressure, mm Hg
$\mathbf{q}_h$	heat flux, cal cm^{-2} sec^{-1}
$\mathbf{q}_l$	liquid flux, g cm^{-2} sec^{-1}
$\mathbf{q}_m$	$= \mathbf{q}_l + \mathbf{q}_v$ moisture flux, g cm^{-2} sec^{-1}
$\mathbf{q}_v$	vapor flux, g cm^{-2} sec^{-1}
R	gas constant of water vapor, erg g^{-1} °C^{-1} (=4.615 × 10^6)
S	porosity, cm^3/cm^3
t	time, sec
T	absolute temperature, °K
T_0	arbitrary reference temperature, °K
W	differential heat of wetting, cal g^{-1}
x	horizontal coordinate, cm
z	vertical coordinate, positive upwards, cm
α	tortuosity factor for diffusion of gases in soils (≈0.67)
β	$= d\rho_0/dT$, g cm^{-3} °C^{-1} (=1.05 × 10^{-6} at 20°C)
γ	temperature coefficient of surface tension of water, °C^{-1} (=−2.09 × 10^{-3} at 20°C)
θ	$= \theta_l + \theta_v$ total volumetric moisture content, cm^3/cm^3
θ_l	volumetric liquid content, cm^3/cm^3
θ_{lk}	value of θ_l at which 'liquid continuity' fails
θ_v	volumetric vapor content, cm^3 of precipitable water/cm^3
λ	thermal conductivity, cal cm^{-1} sec^{-1} °C^{-1}
λ_*	hypothetical thermal conductivity of moist porous medium excluding vapor movement, cal cm^{-1} sec^{-1} °C^{-1}
λ_a	thermal conductivity of air, cal cm^{-1} sec^{-1} °C^{-1}
λ_v	apparent thermal conductivity of an air-filled pore due to vapor diffusion, cal cm^{-1} sec^{-1} °C^{-1}
ν	$= P/(P - p)$ mass flow factor
ρ_v	density of water vapor, g cm^{-3}
ρ_0	density of saturated water vapor, g cm^{-3}
ρ_l	density of liquid water, g cm^{-3}
Ψ	water pressure, with atmospheric pressure as datum, cm
$(\nabla T)_a$	average temperature gradient in air-filled pores, °C cm^{-1}

THE EQUATIONS FOR HEAT AND MOISTURE TRANSFER

Moisture transfer—The equations for the liquid and vapor flux densities as given by *Philip* and *de Vries* [1957] are

$$\mathbf{q}_l/\rho_l = -D_{\theta l}\nabla\theta_l - D_{Tl}\nabla T - K\mathbf{k} \tag{1}$$

$$\mathbf{q}_v/\rho_l = -D_{\theta v}\nabla\theta_l - D_{Tv}\nabla T \tag{2}$$

Combination of these equations leads to the total moisture flux density

$$\mathbf{q}_m/\rho_l = -D_\theta\nabla\theta_l - D_T\nabla T - K\mathbf{k} \tag{3}$$

By application of the continuity principle the following differential equations for θ_l, θ_v and θ are obtained

$$\frac{\partial\theta_l}{\partial t} = -\nabla(\mathbf{q}_l/\rho_l) - E = \nabla(D_{\theta l}\nabla\theta_l) + \nabla(D_{Tl}\nabla T) + \frac{\partial K}{\partial z} - E \tag{4}$$

$$\frac{\partial\theta_v}{\partial t} = -\nabla(\mathbf{q}_v/\rho_l) + E = \nabla(D_{\theta v}\nabla\theta_l) + \nabla(D_{Tv}\nabla T) + E \tag{5}$$

$$\frac{\partial\theta}{\partial t} = -\nabla(\mathbf{q}_m/\rho_l) = \nabla(D_\theta\nabla\theta_l) + \nabla(D_T\nabla T) + \frac{\partial K}{\partial z} \tag{6}$$

Eq. (1), (2), (3), and (6) are identical with (12), (7), (20), and (23) respectively of the paper cited with the exception that in the latter no distinction between θ and θ_l was made. The possibility of water transfer from the liquid to the vapor phase is recognized by the introduction of an 'evaporation' term, $\pm E$, on the right hand sides of (4) and (5). In the case of condensation E is negative, of course.

Assuming that at every instant liquid water is in equilibrium with water vapor the following relation between θ_v and θ_l holds

$$\theta_v = (S - \theta_l)\rho_v/\rho_l = (S - \theta_l)\rho_0 h/\rho_l \tag{7}$$

Hence

$$\frac{\partial\theta_v}{\partial t} = \left[\frac{(S-\theta_l)\rho_0 gh}{\rho_l RT}\frac{\partial\Psi}{\partial\theta_l} - \frac{\rho_v}{\rho_l}\right]\frac{\partial\theta_l}{\partial t} + \frac{(S-\theta_l)h\beta}{\rho_l}\frac{\partial T}{\partial t}$$

$$= \left[\frac{D_{\theta v}}{\alpha v D_{\text{atm}}} - \frac{\rho_v}{\rho_l}\right]\frac{\partial\theta_l}{\partial t} + \frac{(S-\theta_l)h\beta}{\rho_l}\frac{\partial T}{\partial t} \qquad (8)$$

On the right hand side of (8) a term with $\partial h/\partial T$ has been neglected. Philip and de Vries argued that this term is negligible in comparison with the second term on the right hand side of (8).

The value of E follows immediately from (5) and (8). Substitution in (4) leads to the following equation in θ_l and T

$$\left(1 + \frac{D_{\theta v}}{\alpha v D_{\text{atm}}} - \frac{\rho_v}{\rho_l}\right)\frac{\partial\theta_l}{\partial t} + \frac{(S-\theta_l)h\beta}{\rho_l}\frac{\partial T}{\partial t} = \nabla(D_\theta\nabla\theta_l) + \nabla(D_T\nabla T) + \frac{\partial K}{\partial z} \qquad (9)$$

Heat transfer—The heat flux density will be tentatively expressed as follows

$$\mathbf{q}_h = -\lambda_*\nabla T + L_0\mathbf{q}_v + c_p(T - T_0)\mathbf{q}_v + c_l(T - T_0)\mathbf{q}_l \qquad (10)$$

The first term on the right hand side represents the contribution of pure heat conduction; λ_* is the thermal conductivity of the porous medium in the hypothetical case where no moisture movement occurs. The second term represents the transfer of latent heat by vapor movement. The third and fourth terms represent the transfer of sensible heat in vapor and liquid form respectively. T_0 is an arbitrary reference temperature, L_0 is the heat of vaporization at T_0. The tentative character of (10) arises from the fact that the various terms on its right hand side have been considered as additive, which is strictly not permissible as will be discussed below. Further it has been assumed that heat transfer by convection and radiation is negligible, which is usually the case [*de Vries*, 1952a].

The total heat content per unit of volume is

$$C_d(T - T_0) + L_0\rho_l\theta_v + c_p\rho_l\theta_v(T - T_0) + c_l\rho_l\theta_l(T - T_0) - \rho_l\int_0^{\theta_l} W\,d\theta_l \qquad (11)$$

where C_d is the volumetric heat capacity of the dry medium and W the differential heat of wetting. According to thermodynamic theory [*Edlefsen* and *Anderson*, 1943]

$$jW = RT^2\partial\ln h/\partial T = -g(\Psi - T\partial\Psi/\partial T) \qquad (12)$$

Applying the principle of heat conservation we have

$$C\frac{\partial T}{\partial t} + L_0\rho_l\frac{\partial\theta_v}{\partial t} + c_p\rho_l(T - T_0)\frac{\partial\theta_v}{\partial t} + c_l\rho_l(T - T_0)\frac{\partial\theta_l}{\partial t} - \rho_l W\frac{\partial\theta_l}{\partial t} = -\nabla\mathbf{q}_h$$

$$= \nabla(\lambda_*\nabla T) - L_0\nabla\mathbf{q}_v - c_p(\mathbf{q}_v\nabla T) - c_l(\mathbf{q}_l\nabla T) - c_p(T - T_0)\nabla\mathbf{q}_v - c_l(T - T_0)\nabla\mathbf{q}_l \qquad (13)$$

Using (4), (5) and the relation

$$L(T) = L_0 - (c_l - c_p)(T - T_0) \qquad (14)$$

this reduces to

$$C\frac{\partial T}{\partial t} - \rho_l W\frac{\partial\theta_l}{\partial t} = \nabla(\lambda_*\nabla T) - L\rho_l E - c_p(\mathbf{q}_v\nabla T) - c_l(\mathbf{q}_l\nabla T) \qquad (15)$$

where the reference temperature no longer occurs.

Combining (1), (2), (4), (5), (8), (12) and (15) we obtain

$$[C + L(S - \theta_l)h\beta]\frac{\partial T}{\partial t} + \left[\frac{L\rho_l D_{\theta v}}{\alpha v D_{\text{atm}}} - L\rho_v + \rho_l j^{-1}g\left(\Psi - T\frac{\partial\Psi}{\partial T}\right)\right]\frac{\partial\theta_l}{\partial t}$$

$$= \nabla[(\lambda_* + L\rho_l D_{Tv})\nabla T] + L\rho_l\nabla(D_{\theta v}\nabla\theta_l) + \rho_l c_p[(D_{\theta v}\nabla\theta_l + D_{Tv}\nabla T)\nabla T] + \rho_l c_l[(D_{\theta l}\nabla\theta_l + D_{Tl}\nabla T + K\mathbf{k})\nabla T] \qquad (16)$$

The third term on the right hand side of (16), representing sensible heat transfer by vapor movement, is usually negligible.

In the present treatment it has been tacitly assumed that all processes of heat transfer take place uniformly throughout the porous medium, and that sources and sinks of heat (arising from evaporation-condensation and wetting-drying) are distributed uniformly as well. The former assumption is already implicit in the additive structure of the right hand side of (10). However, in reality vapor transfer takes place only in the air-filled pore space, liquid movement only in the water-filled pore space, while evaporation and condensation occur at the water-air interfaces. A complete analytical treatment of these processes would lead us to a 'microscopic' study of heat and moisture transfer in porous media. In such a complete theory the pore geometry has to be specified and proper boundary conditions must be introduced at all the solid-liquid and liquid-gas interfaces. Such

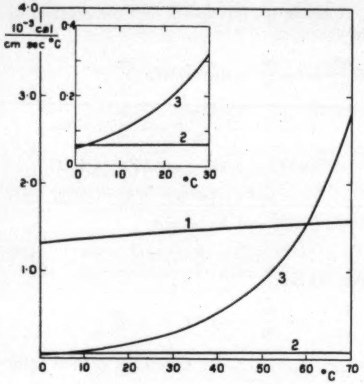

FIG. 1 – Thermal conductivities of water (curve 1) and air (curve 2) and values of $\nu\beta LD_{\mathrm{atm}}$ (curve 3) in relation to temperature; the inset has an enlarged scale of ordinates

an analysis will be extremely difficult and it will not be attempted here.

An exception will be made for vapor distillation due to temperature gradients in the air-filled pores. *Krischer* and *Rohnalter* [1940] have shown that this leads to an apparent increase in the thermal conductivity of the air-filled pores. This theory was incorporated by *de Vries* [1952ab] in a theoretical method for calculating the thermal conductivity of porous media. In this method the conductivity of the air-filled pores is expressed as

$$\lambda_a + \lambda_v = \lambda_a + h\nu\beta LD_{\mathrm{atm}} \tag{17}$$

and the usual boundary conditions of continuity of temperature and (apparent) heat flux at the interfaces are used. Numerical values of $\nu\beta LD_{\mathrm{atm}}$ are given in Figure 1 together with values of the thermal conductivities of water and air. Experimental evidence in support of this theory has also been given by *Krischer* and *Rohnalter* [1940] and *de Vries* [1952ab].

As an alternative to the tentative formulation given above we can therefore replace the expression $\lambda_* + L\rho_l D_{Tv}$ in the first term on the right hand side of (16) by λ, this being the apparent conductivity of the medium including the effect of vapor distillation due to temperature gradients. (It will be noted that $\lambda \neq \lambda_* + L\rho_l D_{Tv}$, because the heat fluxes in different parts of the medium are not additive). This leads to the following revised forms of Eqs. (10) and (16)

$$\mathbf{q}_h = -(\lambda - L\rho_l D_{Tv})\nabla T + L\mathbf{q}_v + c_l(T - T_0)\mathbf{q}_m \tag{18}$$

and (with the omission of the term with c_p)

$$[C + L(S - \theta_l)h\beta]\frac{\partial T}{\partial t} + \left[\frac{L\rho_l D_{\theta v}}{\alpha\nu D_{\mathrm{atm}}} - L\rho_v + \rho_l j^{-1}g\left(\Psi - T\frac{\partial\Psi}{\partial T}\right)\right]\frac{\partial\theta_l}{\partial t}$$
$$= \nabla(\lambda\nabla T) + L\rho_l\nabla(D_{\theta v}\nabla\theta_l) + \rho_l c_l \cdot[(D_{\theta l}\nabla\theta_l + D_{Tl}\nabla T + K\mathbf{k})\nabla T] \tag{19}$$

In (18) use has been made of (14) to eliminate L_0, this can of course be done in either formulation.

It might appear arbitrary to single out the particular term arising from vapor distillation due to temperature gradients. However, this term often represents the most important contribution of moisture movement to the heat transfer. Since it increases the conductivity of the poorest conducting part of the system (namely, the gaseous part) it contributes markedly to the overall conductivity of the porous medium. From (17) and Figure 1 it follows, for instance, that in the temperature range of 0° to 40°C the conductivity of the air-filled pores can be increased by a factor 2 to 9 by the vapor contribution.

The second term on the right hand side of (19) also arises from vapor diffusion, this time under the influence of moisture gradients. Since the corresponding heat flux is not proportional to ∇T it cannot be incorporated in λ in the same way as the term $\nabla(L\rho_l D_{Tv}\nabla T)$.

For the present we shall consider (10) with (16), and (18) with (19) as equivalent alternatives. We shall discuss the applicability of each of these alternatives further in the following section.

Eq. (9) and (16) or (19) govern the simultaneous transfer of moisture and heat in porous media. Eq. (16) or (19) replaces the Fourier equation of heat conduction. They are more general than (24) in the paper of Philip and de Vries; (19) reduces to the latter when heat transfer by liquid movement is negligible and $W = \partial\theta_v/\partial t = 0$. The generation of heat due to viscosity of the moving liquid has been neglected in the present treatment. It would give rise to an additional term $gq_l^2/j\rho_l K$ on the right hand sides of (16) and (19). This term is negligible under most circumstances. Eq. (9) is more general than (23) in the previous paper. Note that the coefficients occurring in these equations are functions of the dependent variables, θ_l and T. They all depend strongly on θ_l. Their variation with T is less outspoken except for $D_{\theta v}$ and D_{Tv} which both increase rapidly with increasing temperature.

For the sake of completeness we must point out that the present theory cannot be applied in cases where hysteresis operates [*Philip*, 1955].

Numerical values of the various diffusivities occurring in these equations can be calculated once Ψ and K are known as functions of θ_l. The thermal properties (λ and C) of a soil can be calculated from its composition as discussed by the author [*de Vries*, 1952ab].

Values of the diffusivities for Yolo light clay (a clay loam) were published by *Philip* [1955, 1957c] and *Philip* and *de Vries* [1957]. These are based on measurements of Ψ and K by *Moore* [1939]. *Philip* [1955] extrapolated the Ψ and K curves at the low end of the moisture range. The thermal conductivity of this soil in relation to θ_l, as calculated by the author, was also published by *Philip* [1957c]. Its heat capacity is: $C = 0.23 + \theta_l$.

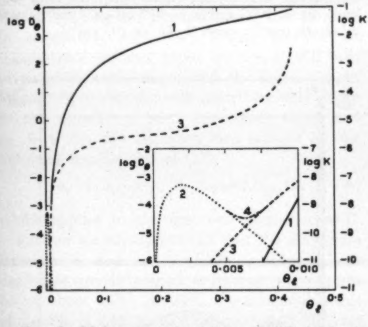

FIG. 2 – Moisture conductivity and diffusivities in relation to moisture content θ_l for a medium sand at 20°C; curve 1, K(cm sec^{-1}); curve 2, $D_{\theta v}$ (cm^2 sec^{-1}); curve 3, $D_{\theta l}$ (cm^2 sec^{-1}); curve 4, $D_\theta = D_{\theta v} + D_{\theta l}$

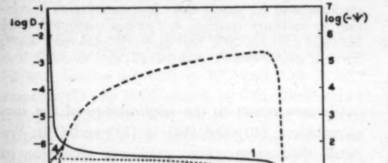

FIG. 3 – Water pressure and thermal moisture diffusivities in relation to moisture content, θ_l, for a medium sand at 20°C; curve 1, Ψ (cm); curve 2, D_{Tv} (cm^2 sec^{-1} °C^{-1}); curve 3, D_{Tl} (cm^2 sec^{-1} °C^{-1}); curve 4, $D_T = D_{Tv} + D_{Tl}$

Since the numerical values will be used only for illustrative purposes we are here not so much concerned with the exact values of the various quantities as with their order of magnitude and in the way they change with θ_l and T.

To illustrate the influence of soil texture values for a sand (particle sizes 0.01 to 0.06 cm) are given in Figures 2 and 3. Values of λ and Ψ in relation to θ_l for this sand were determined by the author [*de Vries*, 1952a]. Its heat capacity, $C = 0.27 + \theta_l$. Values of K were calculated from the $\Psi(\theta_l)$ curve by the method of *Childs* and *Collis-George* [1950]. The calculations were formally extended to θ_l-values as low as 0.006, although it is very doubtful whether the procedure is still applicable at such low moisture contents. This was necessary because the results indicate that moisture movement in the liquid and the vapor phase are of the same order of magnitude in the moisture range $0.006 < \theta_l < 0.02$ (assuming the order of magnitude of the calculated K values to be correct). The value 0.10 was chosen for θ_{lK}. All numerical values given here are for 20°C.

It follows from the equations that true equilibrium in the soil requires that both the total potential ($= \Psi + z$; the influence of soluble salts is left out of consideration here) and the temperature are constant. In a non-equilibrium state there will always be interaction between heat and moisture transfer, even if initially the temperature gradient were zero.

It can be easily checked that for such processes as infiltration of water available in excess at the soil surface and water movement leading to evaporation from bare soil at rates of the order of 10^{-6} g cm^{-2} sec^{-1} or more the dominant term on the left hand side of (9) is $\partial\theta_l/\partial t$, while the term $\nabla(D_T \nabla T)$ on the right hand side is small in comparison with the other terms. These processes can therefore be regarded as isothermal to a good degree of approximation [*Philip*, 1957ab]. When q_m is of the order of 10^{-7} g cm^{-2} sec^{-1} or less moisture movement due to temperature gradients is no longer negligible [*Philip*, 1957c; *de Vries*, 1957].

Similarly in soils under natural conditions the dominant terms in (19) are often $C\partial T/\partial t$ and $\nabla(\lambda \nabla T)$.

As an application of the present theory we shall discuss steady state heat conduction in a moist soil in greater detail in the following section.

STEADY STATE HEAT CONDUCTION

We shall assume that an experiment in heat conduction is carried out in which both θ_l and T vary either in a horizontal direction or in a vertical direction and that a steady state has been reached ($\partial\theta_l/\partial t = \partial T/\partial t = 0$). The steady state will be characterized by the magnitudes of the moisture flux q_m and the heat flux q_h in the sample.

The moisture and the temperature gradient can be solved from (2), (3) and (18). For the 'vertical' case we find

$$\frac{d\theta_l}{dz} = \frac{q_h D_T - K\lambda - q_m c_l (T - T_0) D_T - q_m \lambda/\rho_l}{\lambda D_\theta - L\rho_l D_{\theta v} D_T} \tag{20}$$

$$\frac{dT}{dz} = -\frac{q_h D_\theta - K L \rho_l D_{\theta v} - q_m c_l (T - T_0) D_\theta - q_m L D_{\theta v}}{\lambda D_\theta - L\rho_l D_{\theta v} D_T} \tag{21}$$

Similar equations for the 'horizontal' case are obtained by substituting x for z and 0 for K. In the alternative formulation (starting from (10) instead of (18)) we must substitute $\lambda_* + L\rho_l D_{Tv}$ for λ.

In thermal conductivity experiments the soil sample is usually bounded by solid surfaces [for example, *Kersten*, 1948] and in this case $q_m = 0$ in the steady state. For the horizontal case (20) and (21) then reduce to

$$\frac{d\theta_l}{dx} = \frac{q_h D_T}{\lambda D_\theta - L\rho_l D_{\theta v} D_T} \tag{22}$$

$$\frac{dT}{dx} = -\frac{q_h D_\theta}{\lambda D_\theta - L\rho_l D_{\theta v} D_T} \tag{23}$$

The apparent thermal conductivity found in an experiment of this type is therefore $\lambda - L\rho_l D_{\theta v} D_T/D_\theta$, or $\lambda_* + L\rho_l(D_{Tv} D_{\theta l} - D_{\theta v} D_{Tl})/D_\theta$ in the alternative formulation.

Values of $d\theta_l/dx$ and dT/dx calculated from (22) and (23) for Yolo light clay and the sand of Figures 2 and 3 are given in Figures 4 and 5. They hold for 20°C and $q_h = 10^{-3}$ cal cm^{-2} sec^{-1}. It will be seen that the moisture gradient in the sample is very small, except in the θ_l region where D_T is not small in comparison with D_θ. This region is narrower and at a lower average moisture content for the coarser textured soil than for the soil of finer texture. Values of $\theta_l(x)$ and $T(x)$ can be obtained by numerical integration of (22) and (23) for given boundary conditions.

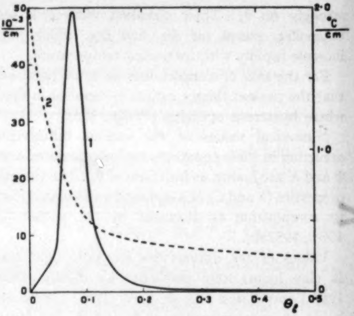

FIG. 4 – Moisture and temperature gradients in Yolo light clay for steady state heat conduction in relation to moisture content, θ_l; values computed from (22) and (23) for 20°C and $q_h = 10^{-3}$ cal cm^{-2} sec^{-1}; curve 1, $d\theta_l/dx$ (cm^{-1}); curve 2, dT/dx (°C cm^{-1})

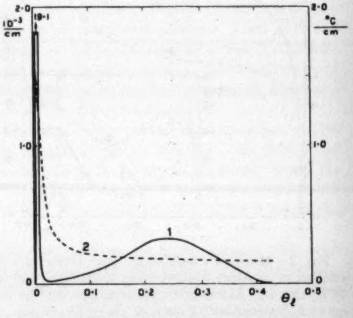

FIG. 5 – Moisture and temperature gradients in a medium sand for steady state heat conduction in relation to moisture content, θ_l; values computed from (22) and (23) for 20°C and $q_h = 10^{-3}$ cal cm^{-2} sec^{-1}; curve 1, $d\theta_l/dx$ (cm^{-1}), curve 2, dT/dx (°C cm^{-1})

We now revert to the applicability of the two alternatives, (10) and (16) or (18) and (19). We recall that temperature gradients give rise to moisture movement in the vapor and the liquid phase of which the former contributes most to the heat transfer. In steady state experiments with $q_m = 0$ there will be a return moisture flow of equal magnitude due to moisture gradients. We now distinguish the following three θ_l regions.

The region where $D_{\theta l} \gg D_{\theta v}$.—In this case the return flow is almost entirely in the liquid phase. Vapor diffusion due to temperature gradients will contribute fully to the heat transfer and equation (18) must be preferred. It will be noted that in this region $L\rho_l D_{\theta v} D_T / D_\theta \ll \lambda$, so that the apparent conductivity measured in an experiment of this type is the same as that predicted by the theory based on (17).

The region where $D_{\theta l} \ll D_{\theta v}$—Here moisture movement is almost exclusively in the vapor phase, as it can be easily checked that D_{Tl} is also small in comparison with D_{Tv} in this region. There will be no net vapor movement and (10) must therefore be used. Eq. (22) and (23) now reduce to

$$d\theta_l/dx = q_h D_{Tv}/\lambda_* D_{\theta v} \qquad (24)$$

$$dT/dx = -q_h/\lambda_* . \qquad (25)$$

The region where $D_{\theta l}$ and $D_{\theta v}$ have comparable magnitudes—In this region D_{Tl} will still be small in comparison with D_{Tv}. Return flow to the temperature induced vapor movement will take place both in the vapor and the liquid phases. Hence, vapor diffusion will contribute only partly to the transfer of heat. For steady states and $q_m = 0$ this can be taken into account by the following modification of (17)

$$\lambda_a + \lambda_v = \lambda_a + D_{\theta l} h \nu \beta L D_{atm}/D_\theta \qquad (26)$$

which applies to the first two regions as well.

Further we must point out that the differences between λ and $\lambda_* + L\rho_l D_{Tv}$, although not negligible, are fairly small, at least at temperatures below about 30°C. At 20°C the maximum value of $L\rho_l D_{Tv}$ is 0.15×10^{-3} cal cm^{-1} sec^{-1} °C^{-1} for both the sand and Yolo light clay. This is small in comparison with λ (or λ_*) except at low moisture contents. The difference between λ and λ_* is generally of the same order of magnitude as $L\rho_l D_{Tv}$. For instance, for the sand at 20°C and $\theta_l = 0.09$ the (calculated and measured) value of λ is 4.38×10^{-3}, while the (calculated) values of λ_* and $L\rho_l D_{Tv}$ are 4.06×10^{-3} and 0.14×10^{-3} respectively. At 20°C and $\theta_l = 0.01$ these values are: $\lambda = 0.90 \times 10^{-3}$, $\lambda_* = 0.64 \times 10^{-3}$ and $L\rho_l D_{Tv} = 0.15 \times 10^{-3}$. However, $L\rho_l D_{Tv}$ increases rapidly with increasing temperature and at 60°C, for instance, its maximum value is about 1.0×10^{-3} cal cm^{-1} sec^{-1} °C^{-1}.

The situation is more complicated for steady state conditions in the 'vertical' case or when $\mathbf{q}_m$ is not zero. Then $\mathbf{q}_h$ is no longer strictly proportional to ∇T. The outcome of a thermal conductivity experiment, for instance, will depend on the boundary conditions for moisture flow and on the direction of the temperature gradient. However, K is practically zero in the second region and there is no difference between transfer of heat and moisture in horizontal and vertical directions in this region.

Under non-stationary conditions (16) or (19) must be used with proper initial and boundary conditions. Here also $\mathbf{q}_h$ will not be proportional to ∇T. An analysis of non-stationary experiments for determining the thermal conductivity using cylindrical probes will be published elsewhere (*de Vries* and *Peck* [1958ab]).

Under most circumstances it will be best to apply (18) and (19) in the first region. For the second and third regions the choice between the alternative formulations must be decided upon by a careful consideration of the experimental conditions. If, for instance, water is supplied at a sufficient rate, while $\mathbf{q}_m$ and $\mathbf{q}_h$ are in the same direction (18) and (19) can be applied over the entire range of moisture contents.

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Calculation of Total and Component Potentials of Water in Soil*

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Abstract—The total potential of water in moist soil is assumed to be the sum of gravitational, pressure, osmotic and adsorption components. Osmotic potential is related to solute concentration at any point. Adsorption potential is assumed to depend on interaction of water dipoles with electric fields associated with the solid-liquid interface. The Gouy-Chapman theory of the electric double layer provides a basis for computing both osmotic and adsorption potentials at any point in the liquid outside the first few monolayers of water enveloping soil particles. From these, pressure potential can be calculated. Curves illustrating the variation of component potentials with distance from a particle are presented along with curves relating total potential to film thickness for soils brought to hydraulic equilibrium or to vapor equilibrium with external solutions. Measurement of total potential by freezing point depression is questioned.

INTRODUCTION

It was logical that *Buckingham's* [1907] original concept of the capillary potential of soil moisture would be extended to include not only the pressure and gravitational components, but also the effects of solutes and force fields other than gravity. *Edlefsen* (then Chairman of the Committee on Soil Moisture, AGU) and *Anderson* [1943], in their monumental *Thermodynamics of soil moisture*, considered these effects in detail, introducing the concepts of the total specific free energy (equivalent to total potential) of soil moisture, and its components due to pressure, solutes, and force fields. The force field was regarded as the sum of the gravitational field and any other body-force fields present.

Edlefsen and Anderson did not attempt to specify the force field emanating from an individual soil grain but presumed that it behaved in more or less the same fashion as the gravitational field of the Earth, that is, a field that declines monotonically with distance, reaching its zero value at infinite distance. They pointed out that the variation of this field with distance from the soil grain was "... assumed by various investigators to obey anything from the inverse square law to an inverse fifth law...." They also observed that the force field was probably electrical. Lacking a description of the force field, they could only include its effects in their equations in a purely formal manner, placing a severe limitation upon their other achievements.

An entirely new approach was introduced by *Schofield* [1946] who, using the Gouy-Chapman theory of the electric double layer, calculated a relationship between the thickness of a water film on a charged surface and the osmotic pressure at the film surface. Assuming, as Schofield did, that at this film surface only the osmotic potential and the pressure potential differ from their standard values, one can calculate the pressure at the film surface as a function of the film thickness. Using some experimental data from literature sources, Schofield showed that good agreement was found for water films on mica, although apparently poor agreement was found for dilute solutions of NaCl on lead glass. More recent experiments with silicate clay minerals [*Bolt* and *Miller*, 1955; *Bolt*, 1956; *Warkentin* and others, 1957] provide instances of remarkable agreement between theory and experiment, indicating that, in principle, the assumption that the adsorption potential vanishes at the film surface is correct in selected cases. A closer examination of the nature of the adsorption potential shows indeed that, excepting the first few layers of water molecules adsorbed on the surface, the adsorption forces are proportional to the square of the electric-field intensity. These forces thus become equal to zero both at the film surface and, in regions where no phase boundary between water and air occurs, at some location between opposing solid-liquid interfaces. In their treatment of adsorptive force fields, Edlefsen and Anderson did not anticipate this critical consequence of the application of the double-layer theory and, as a result, the need for much of the more complicated and unrewarding part of their analysis disappears.

This paper presents a recombination of Buckingham's capillary potential concept and the thermodynamic analysis of Edlefsen and Anderson with Schofield's application of the theory of the electric double layer to soil water systems, together with numerical results for some appropriate systems.

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* Contribution from the Department of Agronomy, New York State College of Agriculture, Cornell University, Ithaca, N. Y. as Agronomy Paper No. 431.

THE TOTAL SOIL MOISTURE POTENTIAL

Thermodynamic and mechanical analyses of the energetics of water in soil give results which are identical except in form. *Edlefsen* and *Anderson* [1943] and recently, *Low* and *Deming* [1953] use thermodynamic variables for their analyses. We elect to use the notation and terminology of mechanics.

The total potential is defined as the minimum energy per gram of water which must be expended in order to transport an infinitesimal test body of water from a specified reference state to any point within the liquid phase of a soil-water system which is in a state of rest. The reference state is commonly taken to be a pool of pure water at the same temperature with a flat surface exposed to atmospheric pressure at a known elevation. Under conditions in which the soil will spontaneously adsorb water from the reference state, the potential is a negative quantity. In any soil-water system in a state of rest, the total potential does not vary from point to point in the system.

The total potential Ψ depends upon the force fields which act upon the test body of water as the transfer is made. These forces are presumed to be: gravity, the pressure-gradient force, the diffusion or osmotic-pressure gradient force, and an electrical 'adsorption' force. If the force per gram mass of water is represented by the vector $\mathbf{F}$, the work done against these forces is

$$\Psi = -\int \mathbf{F}_g \cdot d\mathbf{l} - \int \mathbf{F}_p \cdot d\mathbf{l} - \int \mathbf{F}_{0p} \cdot d\mathbf{l} - \int \mathbf{F}_a \cdot d\mathbf{l} \quad (1)$$

where $d\mathbf{l}$ is an infinitesimal displacement vector along the path taken by the test body. The respective integrals will be represented by the symbols ζ, φ, ω, and α and will be called the gravitational potential, the pressure potential, the osmotic potential, and the adsorption potential, respectively. In some instances centrifugal-force fields may be involved and an additional term may be added. Temperature gradients, if present, introduce special problems which will not be considered in this treatment.

The gravitational potential—The force per gram of water exerted by the Earth's gravitational field is the vector

$$\mathbf{F}_g = -g\mathbf{k} \quad (2)$$

where $\mathbf{k}$ is a unit vector in the z direction, positive upwards. The negative sign indicates that the gravitational force acts in the opposite (downward) direction. The strength of the gravitation field is the scalar g.

Thus

$$\zeta = g\int \mathbf{k} \cdot d\mathbf{l} = g\int dz \quad (3)$$

The pressure potential—The force per gram acting on water in a pressure field is the vector

$$\mathbf{F}_p = -v\nabla p \quad (4)$$

where v is the specific volume (reciprocal density) of the water. The minus sign indicates that the force acts in a direction of decreasing pressure. Thus

$$\varphi = \int \nabla p \cdot d\mathbf{l} = v\int dp \quad (5)$$

The osmotic potential—When two solutions of unequal concentration are in communication via a semipermeable membrane, the effects of the diffusion force are apparent. If the volumes of both phases are held constant, the pressure will increase in the more concentrated solution until it exceeds the pressure in the less concentrated solution by an amount equal to the difference in the osmotic pressures of the two solutions. If the membrane is visualized as possessing a concentration gradient, then it is apparent that, at equilibrium, the pressure gradient force on water in the membrane just balances the osmotic pressure gradient force (or diffusion force). In the following discussion it will be assumed that the increment of osmotic pressure of the solutions is independent of pressure. It follows that

$$\mathbf{F}_{0p} = v\nabla\Pi \quad (6)$$

where Π is the osmotic pressure. The positive sign indicates that the force acts in the direction in which Π increases. Thus

$$\omega = -v\int \nabla\Pi \cdot d\mathbf{l} = -v\int d\Pi \quad (7)$$

The adsorption potential—Attractive (adsorptive) forces between solids and water can be divided in two categories, short-range forces and long-range forces. To the first category belong chemical forces (caused by localized interactions between the electron clouds of surface atoms and water molecules) and London-van der Waals' forces which are due to the interaction of transient electric fields arising from the relative motion of the atom nuclei and their electron clouds. The latter forces, although not as localized as the chemical forces, are in the case of interaction between water and a solid surface still of short range as a result of the destructive interference with fields from other atoms as the distance between the atoms under consideration increases. Although such forces account for the cohesive strength of the water and the phenomenon of surface tension, it seems unlikely that the effective range with regard to the adsorption of water on solid surfaces extends beyond the first few molecular layers adjacent to the interface.

In contrast to these short-range forces, the long-range forces, which are due to the interaction of the water dipoles with the electrostatic field emanating from a charged solid surface, may easily extend beyond 100 A. It seems reasonable, therefore, to ignore the effects of the short-range forces in the soil-water systems, except at low water contents usually encountered only in the laboratory.

The interaction between a polar or polarizable medium and electrostatic field is discussed extensively in textbooks [*Harnwell*, 1938]. A nonuniform field exerts a net translational force on a dipole as a result of the difference in field intensity at the two poles of the dipole. The magnitude of this force depends upon (1) the degree of polarization of the water, which, if the field is not too intense (to avoid dielectric saturation), is simply proportional to the field intensity, and (2) the space rate of change of the field intensity. According to standard text books, the energy of a polar medium associated with this force is equal to

$$\alpha = -\frac{\epsilon - 1}{8\pi} v \int d(\nabla\psi)^2 \qquad (8)$$

where ϵ is the dielectric constant (assumed to be independent of the field intensity, see *Bolt* [1955]) and ψ is the electric potential.

Notice that the adsorption energy is always a negative energy if the field intensity differs from zero and the dielectric constant exceeds unity. The magnitude of the field intensity at certain locations in a soil-water system may be approximated with the aid of the Gouy-Chapman theory of the electric double layer.

THE ELECTRIC DOUBLE LAYER

Details of the Gouy-Chapman theory mentioned above have been presented by *Schofield* [1946], *Verwey* and *Overbeek* [1948], *Bolt* [1955], and others. In effect, this theory assumes that when a segregation of charge occurs at a solid-liquid interface, the ions present in the liquid phase are acted on (1) by a diffusion force which tends to scatter all solute species uniformly throughout the solution, and (2) by Coulombic forces which tend to distribute the ions in a manner which will minimize the electric potential differences occurring in the system or, in effect, minimize the segregation of charges.

Equating these forces, one may write

$$-v\nabla\Pi = v\rho\nabla\psi \qquad (9)$$

where ρ is the net electrical charge per unit volume. The minus sign before the left hand term indicates that the diffusion force on the ions present in the double layer acts in the direction in which Π decreases. Observe that when the net charge density ρ is positive, the net Coulombic force on the ion acts in the direction in which ψ decreases, and vice versa.

Introducing the Poisson equation ($\nabla^2\psi = -4\pi\rho/\epsilon$), one obtains

$$\nabla\Pi = \frac{\epsilon}{4\pi}\nabla\psi\nabla^2\psi \qquad (10)$$

This equation cannot be solved in its general form; in the special case of a one-dimensional electric field one finds for arbitrary points m and n

$$\Pi_m = \Pi_n + \frac{\epsilon}{8\pi}[(d\psi/dx)_m^2 - (d\psi/dx)_n^2] \qquad (11)$$

or, if the location n is defined as the point where $(d\psi/dx)$ equals zero

$$(d\psi/dx)_m = \sqrt{\frac{8\pi}{\epsilon}(\Pi_m - \Pi_n)} \qquad (12)$$

This equation may be regarded as the starting equation of the Gouy-Chapman theory of the planar double layer. To complete this theory it is assumed that the double layer ions exhibit ideal behavior (that is, $\Pi = RT\Sigma c$, in which Σc is the combined concentration of all ionic species). It should be emphasized that the Gouy-Chapman theory ignores the detailed structure double layer, for the charges present are finite and the electric field is not truly one-dimensional.

For the spherical symmetrical case, numerical

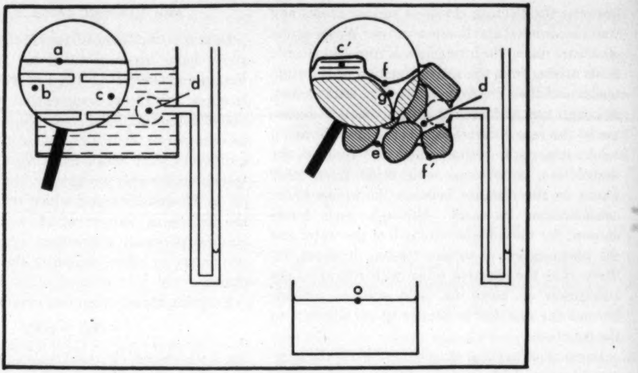

FIG. 1 – Schematic representations of ideal clay-water system (left) and mixed system (right) with points mentioned in the text identified by letter

solutions of (10) can be found in the literature [*Hoskin*, 1953]. In practice, the solution obtained from the planar case becomes acceptable if $\kappa r > 10$, in which r is the radius of curvature of the charged surface; κ is Debye's ionic parameter. This implies that in most soils the planar solution is satisfactory for $r > 1000$ A; in other words, the double layer adjacent to all soil mineral surfaces can be approximated quite well with the planar solution, with the exception of the regions very close to the edges of plate-shaped clay particles. This observation is of importance, for it will be argued that the majority of the moisture present in soils can probably be regarded as moisture present in either planar double layers or in field-free regions in the large interstices.

RELATIONSHIP OF COARSE TO FINE GRAINED SYSTEMS

Classical ideas of water in porous media as exemplified by *Haines'* [1930] analysis assume that all soil grains are supported in place by contact with adjacent grains and that the pore geometry is more or less fixed. When one is given the pore geometry and the surface-tension equation, in principle one can work out all possible configurations of the air-water interface, which are consistent with an arbitrarily chosen pressure in the liquid phase, taking into account the hydrostatic variation of pressure with elevation. An analysis of this type usually acknowledges the presence of an adsorbed film of water on solid surfaces which would otherwise be in direct contact with air.

In contrast to the familiar case described is the ideal clay-water system in which the particles are not in direct contact but are separated by layers of water. Removal of water from such a system does not introduce a third phase but merely causes the particles to move closer to one another with the pores remaining water saturated.

Although both cases may be found in nature, a majority of soils probably represent a mixture of these two extremes with a more or less rigid framework of coarse particles corresponding to the first system described but containing space occupied by systems resembling the latter.

Figure 1 has been drawn to illustrate the essential features of ideal clay, coarse-grained, and mixed systems. In the following sections the component potentials at the various points identified in the figure will be analyzed.

IDEAL CLAY-WATER SYSTEMS

Although particles of clay size occur in a variety of shapes, the common silicate clays evidently possess regular faces which are either planar or a series of planes arranged in terraces. In the lattices of the 2:1 type the particles exist as thin sheets which are usually oriented in a more or less parallel array. For the purposes of this paper an ideal clay-water system will be one in which the particles approximate infinite sheets of uniform thickness in equally spaced, parallel array with interacting double layers which render this the stable configuration. It will also be assumed that the quantity of material present is sufficiently large that the curvature of the air-water interface which bounds the system is negligible. The diagram on the left in Figure 1 is intended to represent such a system. Beginning with the reference pool and considering the points indicated, one finds the following values of the component potentials.

Point o—This point is just inside the liquid phase at the flat surface of the reference pool of pure water. By convention

$$\Psi_0 = z_0 = p_0 = \Pi_0 = \psi_0 = (\nabla\psi)_0 = (\nabla^2\psi)_0 \equiv 0 \quad (13)$$

Point d—This point is found in the 'equilibrium dialyzate' of the soil-water system. This is the liquid which would be found in a tensiometer cup equilibrated with the soil, or which would be obtained by compressing the soil and allowing a small quantity of water to escape at atmospheric pressure through a membrane permeable to water and salts. The gage pressure required to initiate discharge is $-p_d$ where p_d is the normal gage pressure (usually negative) of the equilibrium dialyzate present in a tensiometer cup inserted in the soil. Moreover the 'swelling pressure' which this system can exert on its surroundings when given access to equilibrium dialyzate at atmospheric pressure will be $-p_d$. For an unsaturated system, the 'surroundings' of the soil-water system will be the gas phase.

Formation of bubbles of air and water vapor in a tensiometer cup as p_d decreases limits its useful range to gage pressures greater than about -0.85 atmosphere [*Richards*, 1949]. It seems reasonable to suspect that equilibrium dialyzate would cease to exist in soil cavities when p_d approaches this limit. Thus, equilibrium dialyzate may not exist in soils at low water contents, except when created by ultrafiltration. Whether real or imaginary, equilibrium dialyzate is a useful concept and a reference point for computation.

It follows that at point d,

$$\zeta_d = gz_d; \quad \varphi_d = vp_d; \quad \omega_d = -v\Pi_d;$$
$$\text{and} \quad \alpha_d = 0 \quad (14)$$

Point a—This point is found at the air-water interface at a point of zero curvature. Thus, the absolute pressure at this point is equal to the pressure P_a in the atmosphere at this elevation z_a above the datum level.

P_a can be obtained from the barometric equation for an isothermal atmosphere:

$$P_a = P_0 e^{-Mgz_a/RT} \quad (15)$$

where M is the mean molecular weight of air.

Since the gage pressure p_0 is zero at z_0, one finds at point a,

$$p_a = P_0(e^{-Mgz_a/RT} - 1). \quad (16)$$

Since all of the double-layer ions are confined to the liquid phase (the system as a whole is electrically neutral), $\nabla\psi_a = 0$; hence, $\alpha_a = 0$. This result is the key to this paper and deserves closer attention, for it may not be strictly correct. The Gouy-Chapman theory of the double layer does not consider the fine structure of the electric field within the double layer. Instead, it assumes that local distortions, which must occur in the vicinity of each ion, may be neglected and the field may be represented as one dimensional for planar surfaces. Such a field must vanish at the air-water interface. Nevertheless, it is possible (although unlikely, because of the hydration shells of ions) that the outer-most layer would already contain some double-layer ions. The one-dimensional field would then increase abruptly to a finite value as this layer is traversed. Returning to the microscopic viewpoint, it is apparent that this transition is really localized to the position of the ions and would not occur in the intervening areas. Such localized field distortions would, however, be similar in nature to the distortions to be found around ions at the surface of any neutral electrolyte solution and consequently would be of no concern in a consideration of the over-all electric field. With regard to the latter, it is only inside the first layer that the unbalance of charge becomes significant in terms of the one-dimensional field of the Gouy-Chapman theory.

This argument is at best qualitative, and more detailed analysis may prove it to be inadequate. It presents a working hypothesis consistent with the Gouy-Chapman theory and subject to similar limitations but having potentially equal value as a basis for computation.

Accepting these approximations, one obtains

$$\zeta_a = gz_a; \varphi_a = vP_0(e^{-Mgz_a/RT} - 1);$$
$$\omega_a = -v\Pi_a; \text{ and } \alpha_a = 0 \quad (17)$$

Since $\Psi_a = \Psi_d$, it follows that, if $z_a = z_d$

$$\Pi_a = \Pi_d - p_d \quad (18)$$

For the calculation of Π_a see under point *c*. Notice that all other quantities in (17) are measurable.

Point c—The boundary conditions, applicable to the Gouy-Chapman equations for the double layer which must be applied to obtain a solution for parallel plates separated by a distance $2x_c$, are essentially identical with those which must be applied to a system in which the double layer is terminated by an air-water interface parallel to the particle at a distance x_c. In other words, the double layer between parallel, flat, infinite plates is the combined image and mirror image of the double layer present when a flat air-water interface terminates the double layer at a distance half of that which separates the plates. This comparison breaks down if the dimensions of the clay-water system are very small, so that the pressure at the central plane is affected by surface tension and is significantly larger than atmospheric pressure, which exists at the flat air-water interface.

Thus, for a clay-water paste for a body of material which is not too small

$$\zeta_c = \zeta_a \, ; \varphi_c = \varphi_a \, ; \omega_c = \omega_a \, ; \text{and } \alpha_c = \alpha_a \tag{19}$$

Equations have been worked out for such interacting plates which make it possible to estimate ω_c in terms of the surface density of charge of the mineral surface, the concentration of the equilibrium dialyzate, and the separation of the plates (x_c will be taken to represent either the distance from the mineral surface to the central plane at *c* or the film thickness at *a*).

For symmetric electrolytes and ideal behavior

$$\Pi_c = \Pi_d \cosh y_c \tag{20}$$

where

$$y_c = \frac{\nu F \psi_c}{RT}$$

with ν = valence, F charge per gram equivalent, R the universal gas constant, and T the absolute temperature. The parameter y_c can be evaluated in that case from the complete elliptic integral

$$(x_c + x_1)\sqrt{\frac{4\pi}{\epsilon}\Pi_d} = \frac{2RT}{\nu F} e^{-y_c/2} \int_{\varphi=0}^{\varphi=\pi/2} \frac{d\varphi}{\sqrt{1 - e^{-2y_c}\sin^2\varphi}} \tag{21}$$

The parameter x_1 is determined mainly by the surface density of charge Γ in me/cm², and is given approximately by the relation

$$x_1 \simeq \frac{4}{\nu\beta\Gamma} \tag{22}$$

where $\beta = 8\pi F^2/1000\epsilon RT \simeq 10^{15}$ cm/m mole. x_1 is about $4/\nu$ A for montmorillonite, $2/\nu$ *A* for kaolinite and $1/\nu$ A for illite.

Corresponding values of x_c and y_c have been tabulated elsewhere [*Bolt* and *Miller*, 1955].

Point b—This point is located somewhere between parallel interacting plates, not too close to the periphery.

Again

$$\zeta_b = gz_b \tag{23}$$

and

$$\alpha_b = \frac{\epsilon - 1}{8\pi} v(\nabla\psi)_b^2 \tag{24}$$

We are unable to give explicit expressions for the other components in this case, but the following parametric equations in y may be used

$$\omega_b = \omega_c + \frac{v\epsilon}{8\pi}(\nabla\psi)_b^2 \equiv \omega_d \cosh y_b \tag{25}$$

Again noting that $\Psi_b = \Psi_c$

$$\varphi_b = \varphi_c + g(z_b - z_c) + \frac{v(2\epsilon - 1)}{8\pi}(\nabla\psi)_b^2 \tag{26}$$

For this case y_b can be computed from the relationship

$$(x_b + x_1)\sqrt{\frac{4\pi}{\epsilon}\Pi_d} = \frac{2RT}{\nu F} \cdot e^{-y_c/2} \int^{\arcsin e^{-(y_b - y_c)/2}} \frac{d\varphi}{\sqrt{1 - e^{-2y_c}\sin^2\varphi}} \tag{27}$$

values for the incomplete elliptic integral in this expression are tabulated in standard mathematical tables.

If the dimensions of an ideal clay-water system are reduced until it contains only a few particles, the equations given above must be modified to take into account the effects of surface tension on conditions inside the system. This will be considered under the section entitled, *Mixed systems*.

Coarse-grained systems—There can be little doubt that electrical double layers are developed by coarse-grained particles in contact with water. Thus, the analysis of component potentials in proximity of the surface of a clay-size particle is applicable to the surface of a larger mineral particle with the additional consideration of the curvature at the air-water interface and its influence on the pressure just inside the interface.

Point e—This point is found as a curved air-water interface beyond the range of influence of the double layers of nearby particles. Here the classical concepts based on surface tension and film curvature apply. If the surface tension is τ, and the mean radius of curvature is r_e (taken to be negative when the interface is concave on the air side), the gage pressure at e differs from that in adjacent air by an amount $2\tau/r_e$. This leads to

$$\zeta_e = gz_e; \quad \varphi_e = v\left[P_0(e^{-Mgz_e/RT} - 1) + \frac{2\tau}{r_e}\right];$$

$$\omega_e = -v\Pi_e; \quad \text{and} \quad \alpha_e = 0 \qquad (28)$$

In this case, $\Pi_e = \Pi_d$, which is measureable.

Points f and f′—These points are found at curved air-water interfaces in regions influenced by the double layer. The equations for point f are identical to those for point e with a substitution of subscripts. In this case, Π_f may be obtained from double-layer theory, but it also follows that, if $z_f = z_a = z_d$

$$\Pi_f = \Pi_a + \frac{2\tau}{r_f} = \Pi_d - p_d + \frac{2\tau}{r_f}$$
$$= \Pi_d - 2\tau\left(\frac{1}{r_e} - \frac{1}{r_f}\right) \qquad (29)$$

Observe that the osmotic concentration is greater at a than at f.

Point f' is represented by identical equations, but in this case (positive curvature) the osmotic concentration at f' is greater than at a. Comparing equations for f and f' gives

$$\Pi_f - \Pi_{f'} = 2\tau\left(\frac{1}{r_{f'}} - \frac{1}{r_f}\right) \qquad (30)$$

as a general relation between film curvature and concentration at different points on the air-water interface.

Point d—This point is outside the range of the double layers of nearby particles as in the case of point e, and (28) applies with a substitution of subscripts. The mean radius of film curvature at point e is retained, providing $z_d = z_e$, and one obtains

$$\zeta_d = gz_d; \quad \varphi_d = v\left[P_0(e^{-Mgz_d/RT} - 1) + \frac{2\tau}{r_e}\right];$$

$$\omega_d = -v\Pi_d; \quad \text{and} \quad \alpha_d = 0 \qquad (31)$$

Point g—This point is located somewhere in a fully extended planar double layer. In this case the pressure in the water at the outer extremity of the double layer is determined by the film curvature and the surface tension, but the pressure at point g must be calculated. From (11) it follows that

$$\omega_g = \omega_d + \frac{v\epsilon}{8\pi}(\nabla\psi)_g^2 = \omega_d \cosh y_g \qquad (32)$$

From (8) one obtains

$$\alpha_g = \frac{v(\epsilon - 1)}{8\pi}(\nabla\psi)_g^2 \qquad (33)$$

Since $\Psi_g = \Psi_d$ (cf. (31) and (28))

$$\varphi_g = \varphi_d + g(z_g - z_d) + \frac{v(2\epsilon - 1)}{8\pi}(\nabla\psi)_g^2 \qquad (34)$$

The value of $(\nabla\psi)_g$ can be estimated with the help of the double layer theory. For symmetrical electrolytes and essentially planar surfaces, one finds

$$\psi_g = \frac{RT}{\nu F}\ln\left[\frac{\cosh \nu\sqrt{\beta c_d}(x_1 + x_g) + 1}{\cosh \nu\sqrt{\beta c_d}(x_1 + x_g) - 1}\right] \qquad (35)$$

Mixed systems—If small fragments of an ideal clay-water system are scattered through a coarse-grained system, complications may arise if the clay-water sub-systems are sufficiently small. Probably this is rare in nature, but examination of some consequences is of academic interest.

It has already been shown in the preceding section that where the influence of the double layer is felt at a curved air-water interface, the classical condition of constancy of the mean film curvature no longer applies. Figure 2 represents a single pair of parallel clay plates present in a small droplet of water. The plane AA' bisects the space between the plates. Over most of the plane the osmotic concentration of double-layer ions will be essentially uniform, but near the edges it will decrease to a minimum value at the air-water interface. The electric potential varies accordingly. The pressure will vary in somewhat the same manner, increasing from a minimum value at the air-water interface to a maximum value between the plates. Both normal and radial components of the electric field will be zero in the central region, but the radial component will be finite near the periphery, so that α is finite in this region.

A detailed analysis of this system is impractical at this time, since the structure of the double layer in the peripheral zone is not readily obtained. It is

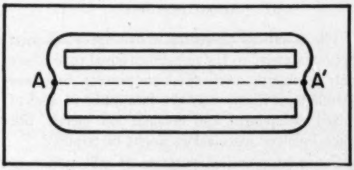

FIG. 2 – Schematic representation of water droplet containing parallel clay plates

apparent, however, that the pressure at every point in this small system will be greater than that in a corresponding large system by an amount no less than $2\tau/r_A$ where r_A is the mean film curvature at A.

A novel consequence of this analysis is that whereas surface tension induces pressure deficits in water present in field-free pores between particles which are in direct contact, it tends to increase the pressure in zero-field regions between particles which are prevented from direct contact with their neighbors by the interaction of their double layers.

It is probable that clay-water sub-systems in mixed systems are generally too large for surface tension to play a significant role in determining the pressure at the central plane between parallel particles, and the assumption that this pressure is atmospheric is probably justified. If this is true, mixed systems have no properties which cannot be estimated from the component parts according to the preceding sections.

NON-IDEAL CLAY WATER SYSTEMS

Expanding lattice minerals are probably the only ones which approach the properties described for ideal clay-water systems. Micaceous minerals, such as illite, might be described as semi-expanding minerals, since repulsive forces act between adjacent particles in the same way as between particles of montmorillonite. The expansion is much less noticeable, since the number of particles per unit volume of solids is much smaller, each particle being an order of magnitude thicker than the individual particles present in montmorillonite. Moreover, micaceous clay minerals can be expected to have terraced rather than simple planar surfaces, so that the distances between opposing faces are not uniform. Blocky or lathlike particles common in kaolinite and attapulgite are even less likely to behave in the manner of the ideal clay-water system described and may approach coarse grained system in general characteristics.

APPROXIMATIONS

The equations presented above apply, at least approximately, to the one-dimensional case where only symmetric electrolytes are present. Standard double-layer theory may also be applied to cases of mixed monovalent and divalent ion species, but some involved calculations might be required.

For most practical purposes it will suffice to proceed as if only symmetric electrolytes were present, and the valence of the electrolyte should be taken as the valence of the cation species present in greatest abundance in the double layer.

If the value of x_c in (21) is small in comparison with $\nu F\sqrt{4\pi/\epsilon\Pi_d}$, (21) and (27) may be simplified, since the concentration of anions between interacting plates will everywhere be small in comparison with cations. In that case, (21), (27), and (12) can be combined to give

$$(d\psi/dx) = \frac{RT}{\nu F}\frac{\pi}{(x_1 + x_c)}\operatorname{cotan}\left[\frac{\pi}{2}\frac{(x + x_1)}{(x_c + x_1)}\right] \quad (36)$$

In Figure 3 examples of the variation of the component potentials in the liquid layer are presented for the case of illite at water contents of approximately 35 pct and 90 pct, dry-weight basis. It is assumed that a symmetric monovalent electrolyte is present with a concentration of 0.01 mol/L in the equilibrium dialyzate.

Figures 4, 5, and 6 have been prepared to show the relationship between x_c, the 'film thickness' for an ideal planar double layer bounded by a flat air-water interface, and the combined solute concentration (moles cations plus moles anions per liter) at the interface. Three different families of curves have been calculated, all having the same (unlabeled) limiting curve for the case of infinitely dilute equilibrium dialyzate. The individual curves

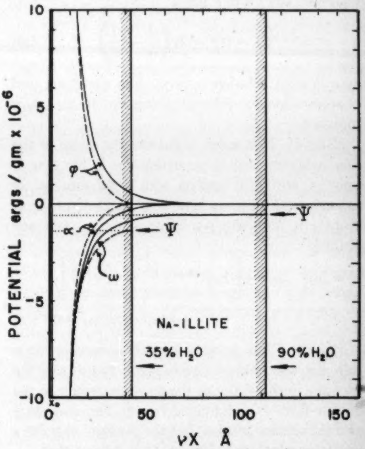

FIG. 3 – Variation of component potentials with distance for ideal clay with film thicknesses corresponding to the indicated water contents

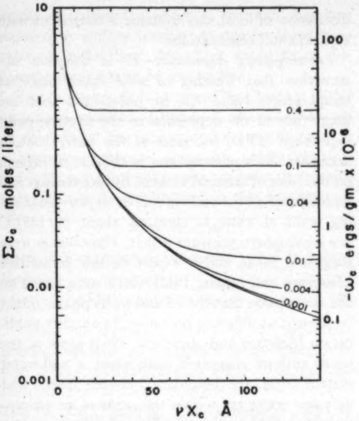

FIG. 4 – Combined concentration at a flat air-water interface bounding a double layer as a function of film thickness x_e and valence ν of the dominant counterion for various nominal concentrations of equilibrium dialyzate in moles/liter; the osmotic component of the total potential at the interface is given on the right-hand ordinate

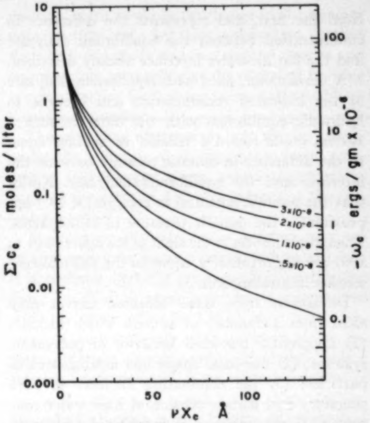

FIG. 5 – Combined concentration and osmotic component of total potential at a flat air-water interface bounding a double layer as a function of film thickness and valence of the dominant counterion for various constant electrolyte contents expressed as milliequivalents of anions per cm² of solid-liquid interface

are labeled according to the nominal concentration of the equilibrium dialyzate in moles per liter.

The first family of curves given (Figure 4) represents relationships calculated for the 'hydraulic-equilibrium case' in which concentration of the equilibrium dialyzate is kept constant. This is intended to simulate the relationship between water content and chamber pressure which might be obtained with a pressure-membrane apparatus in which hydraulic equilibrium is established between water in the soil and equilibrium dialyzate outside the pressure chamber. It is assumed that the membrane is freely permeable to solutes and that the quantity of external solution is such that its concentration is not measurably changed by transfers of water and solutes across the membrane as the system adjusts to equilibrium.

The second family of curves (Fig. 5) represents the relationship calculated for the 'vapor-equilibrium case' in which the quantity of electrolyte present is held constant. Individual curves are identified by the quantity of anions in moles/liter present per unit area of solid-liquid interface in cm².

The third family of curves (Fig. 6) is derived

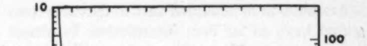

FIG. 6 – Differences between combined concentrations at a flat air-water interface bounding a double layer and the equilibrium dialyzate for various nominal concentrations of equilibrium dialyzate; the corresponding differences in osmotic component of the total potential are indicated on the right-hand ordinate

from the first, and represents the difference in concentration between the equilibrium dialyzate and the flat air-water interface already described.

A tensiometer, filled with equilibrium dialyzate of the indicated concentration and brought to hydraulic equilibrium with the water in such a system would record a 'tension' or 'suction' equal to the difference in osmotic pressure between the interface and the equilibrium dialyzate. Notice that the osmotic potential in ergs/gm $\times 10^{-6}$ approximates the osmotic pressure in atmospheres. Thus, the numbers to the right of the figure (0.01 to 100) are approximately equal to the soil moisture tension in atmospheres.

Deviations from these idealized curves may arise from a number of sources which include: (1) apparently non-ideal behavior of polyvalent systems; (2) non-ideal shape and arrangement of particles; (3) the dominating influence of pore geometry and surface tension at high water contents; (4) the presence of interparticle forces or bonds which interfere with the normal swelling property of planar particles; and (5) segregation of ideal clay sub-systems into minute portions largely enclosed by an air-water interface.

DISCUSSION

Attempts to fit published data to the curves presented have so far been inconclusive. In almost every instance it is possible to force a reasonable fit by making suitable assumptions with regard to details of materials or procedure omitted from the descriptions given. Other reasonable assumptions would lead to a poor fit, and no conclusions may be drawn. Attention is called to the following points which appear to be pertinent to the acceptance of the analysis given.

Swelling pressure—*Warkentin* and others [1957] found that precompressed suspensions of sodium montmorillonite in 10^{-4} m NaCl gave quantitative agreement between the appropriate curve in Figure 6 and experimental results for the range

$$-(\omega_c - \omega_d) = (0.2 \text{ to } 50) \times 10^6 \text{ ergs/gm.}$$

The data show negligible hysteresis except for the initial dewatering leg. On the other hand, similar experments with calcium montmorillonite show rather large discrepancies between theory and measurement. These discrepancies do not necessarily indicate errors in the concept of the forces acting on the water, but do indicate the presence of factors not accounted for by the simple Gouy-Chapman theory of the electrical double layer. These results are taken to be evidence that the discussion of ideal clay systems is consistent with experimental observations.

Freezing-point depression—It is common observation that freezing of soils takes place at temperatures below the ice point, and that the magnitude of the depression of the freezing-point depression (FPD) increases as the water content decreases. This phenomenon is difficult to explain on the basis of classical ideas of surface tension and its influence on the state of soil water, for the freezing point of water is elevated about (1/133)°C per atmosphere pressure deficit. Hypotheses were suggested in an earlier report of this committee [*Anderson* and others, 1942] which were based on the assumption that the ice and water phases might be present at different pressures. In another publication [*Edlefsen* and *Anderson*, 1943] some of the same authors suggested that when a soil-water system froze, the boundary between frozen and unfrozen water lay within the range of an adsorptive force field so that the film of unfrozen water between the ice and the mineral surfaces was compressed and its freezing point lowered accordingly.

These suggestions strain the credulity. It is difficult to imagine co-existing but isolated ice and liquid water phases except in unusual instances. Nor is there any reasonable suggestion regarding the origin of the long range forces which would be required to produce mutual attraction between ice and mineral surfaces across an intervening layer of water.

The present analysis leads to two new concepts to explain depression of the freezing point. First, the modifying influence of the double layer on the concentration of electrolytes present at the ice water interface is taken into account. If it is assumed that the pressure at this interface is atmospheric (as in the simple clay water system described under *Ideal clay-water systems*), the freezing point would be depressed. Moreover, this freezing point depression in ideal systems would be calculable from Π_c according to the relation

$$\text{FPD}_c = 1.86c_c = \frac{1.86\Pi_c}{RT} = \left(\frac{\Pi_c}{12.06}\right)^\circ\text{C} \qquad (37)$$

when Π_c is in atmospheres and c is in moles liter.

The second concept also depends upon the influence of the double layer, which, in the case described for mixed systems, allows surface tension to induce positive pressures in the regions of lowest concentration (and least freezing-point depression). The effect of the double layer upon concentration and, hence, upon FPD would be as before, but to it would be added the effect of increased pressure induced by surface tension. At present there is no basis for belief that this effect would be of sufficient magnitude to be measurable.

Freezing point data obtained by *Campbell* [1952] have been replotted in Figure 7. His samples were equilibrated at the indicated chamber pressures in a pressure membrane apparatus before freezing. Referring to *Ideal clay-water sxstems*, it appears that for samples equilibrated in this manner

$$\Pi_e = \Pi_d - p_d \qquad (38)$$

where the chamber pressure was $-p_d$. It follows that

$$(\text{FPD} \times 12.06 - \Pi_d) = -p_d \qquad (39)$$

Using the osmotic pressure of the saturation extract reported by Campbell as an approximation of Π_d, the ordinate in Figure 7 should approximate the chamber pressure used for equilibration in each sample. The agreement between measured values and a line drawn to represent 1:1 correspondence between these quantities is probably commensurate with the necessarily crude assumptions made.

If it had been assumed that the liquid phase were present at a pressure less than that of the ice phase by the amount indicated on the ordinate, and further assumed that there was no effect of the double layer upon concentration in the soil solution, there would be no change in the appearance of this plot, but this assumption implies that the liquid phase was in a state of tension and was therefore metastable at the observed freezing temperature, for the freezing point is elevated by a decrease in pressure.

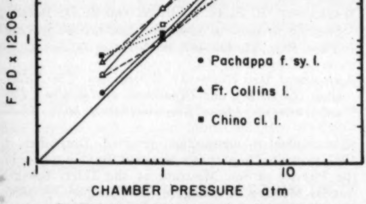

FIG. 7 – Freezing point depression data obtained by Campbell replotted as described in text; open symbols represent unpuddled samples; solid symbols represent puddled samples; samples were equilibrated in a pressure membrane apparatus at the pressure indicated prior to freezing

The remaining alternative, that the ice phase, under the influence of an adsorptive force, compresses the unfrozen water, would require pressures of the order of 150 atmospheres at the ice-water interface.

The pressure at the ice-water interface may not be atmospheric for various mechanical reasons, but it is probable that the pressure effect on freezing point (−1°C/133 atm) is trivial in comparison with the solute effect (−1.86°C/mole/liter). Because of the uncertainty of the pressure at the ice-water interface, freezing point depression, unlike relative vapor pressure, is an inexact measure of the total potential of water in soil. Nevertheless, the principal errors in the freezing point method are probably due to (1) uncertainties in quantity of electrolyte present, (2) the estimation of corrections for the amount of water frozen, and (3) corrections to 'field temperature.' Since the segregation of ice is roughly equivalent to the removal of water by distillation, the curves given in Figure 5 may be used in connection with corrections for the amount of water frozen.

Using Figure 4 to estimate Σc_e at the onset of freezing and Figure 5 to estimate the correction for the amount of water frozen, it should be possible to estimate from one of the points in Figure 7 the freezing points expected at other water contents. Unfortunately, Campbell did not report water contents for the samples frozen and this test of the analysis cannot be applied.

'Tension' in soil water—By convention, water in which the pressure is less than atmospheric is referred to by soil scientists as existing in a state of tension. This is not literally true unless the 'tension' or suction exceeds one atmosphere. It has been shown that water has, at least under favorable conditions, considerable tensile strength. It is also common knowledge that in many systems, especially when the water contains dissolved gases, the tensile strength is apparently nil, for as the absolute pressure approaches the vapor pressure of the water, bubbles of air and water vapor form, 'breaking' the liquid phase. For example, tensiometers used in soil investigations fail as the pressure deficit in the tensiometer cup approaches one atmosphere. It seems likely that the tensile

strength of water in soil would have a similar limitation. This contention should be subject to test, and deserves attention. Recent results of *Lieberman* [1957] encourage the belief that bubbles would be readily nucleated in soil and might persist in quite small pores.

This point is probably academic, however, for the curves shown in Figures 4, 5, and 6 indicate that relatively small proportions of clay-sized particles in a soil can retain substantial quantities of water, comparable to those observed in practice, without resort to the conventional capillary concepts so useful in the case of water retention in large pores. The principles of capillarity apply to micropores but are probably of little consequence in comparison to the retention of water in the double layer itself.

Since previous proposals for explaining the freezing-point depression of water in soil appear untenable and since those advanced in this paper depend upon the presence of double-layer ions, it seems reasonable to suspect that in the range of moisture contents in which freezing-point depressions are measurable, little if any of the water is present in regions in which the double layer is sensibly absent.

We infer that the existence of water in a metastable liquid phase in soils is improbable under ordinary circumstances. We suspect that the fraction of water which is actually in tension is never large except perhaps at very high water contents and small tensions. This conclusion was also reached by Edlefsen and Anderson. We regard apparently large values of soil moisture tension or soil suction to be artifacts accounted for by the influence of the electrical double layer. We acknowledge that it is possible to isolate systems in which water can be made to exhibit great tensile strength, but we doubt that such systems are common in soil.

The discussion presented cannot be regarded as proof of the concepts of the components of the total potential as used in this paper. Instead, the discussion is intended to assist the reader in his evaluation of this analysis as a logical restatement and improvement of earlier ideas. Experimental tests of some of the concepts are possible and it is expected that the value and limitations of this treatment will be demonstrated in due course.

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Typical Solutions of the Differential Equations of Statistical Theories of Flow through Porous Media

A. E. SCHEIDEGGER

Abstract—The description of the miscible displacement process in porous media (such as occurs, for example, during the pollution of ground-water resources with wastes) by methods of statistical mechanics has met with considerable success. The method usually employed is that of considering the motion of each particle through the medium as a random-walk process. Recently, however, it has been suggested that autocorrelation should also be taken into account and a differential equation allowing for this effect to take place has been arrived at. The purpose of the present paper is to give solutions of the autocorrelation equation for some typical cases and to compare the result with that obtained for the random walk model without autocorrelation. These cases refer to the passage of a thin slug of 'tagged' fluid through a porous medium and to the intrusion of a sharp concentration front into a medium. It is shown that autocorrelation has the effect that a concentration-discontinuity proceeds at a finite speed into the medium which cuts off the infinite 'tail' of the solution without autocorrelation. Graphs to illustrate the situation are given.

Introduction—The statistical method has met with considerable success in explaining the experimentally observed effect of dispersion during the passage of a fluid through a porous medium. This effect is particularly important in the displacement of a fluid by another with which it is miscible. Such cases occur during the intrusion of salt water into the fresh-water lens beneath oceanic islands and also during the extraction of petroleum from reservoirs by solvents.

Since statistics were first introduced into displacement studies (for a review, see *Scheidegger* [1957]), a variety of theoretical models has been proposed. Such statistical models rest, as had been outlined earlier, [*Scheidegger*, 1958b] on three types of assumptions: (1) one has to choose an ensemble with which to do statistics; (2) one has to choose the type of statistics which is to be used, and (3) one has to choose the microscopic flow law to which each small volume of fluid is subject. Among the various models that have been proposed, it is of particular interest to weigh those which differ by the type of statistics which they employ, since this is governed by properties of the porous medium. The microscopic flow law depends on the flow regime and on the fluid, but the statistics depends directly on the assumed properties of the porous medium.

A decision between the various possible models can only be made if appropriate experiments are attempted. Experiments that can be performed easily fall into two classes: (1) testing the passage of a thin slug of tagged fluid through a porous medium, and (2) testing the intrusion of an originally sharp front of tagged fluid into untagged fluid. All experiments, of course, refer to linear set-ups; that is, one has only one space coordinate.

In order to provide a basis for comparison of the experiments with the theory, it is necessary to obtain the appropriate solutions of the differential equations for the possible statistical models. It is the purpose of the present paper to do this.

The statistical models—The statistical models that have been proposed to investigate the flow through porous media are essentially two in number.

In both cases one gives a fixed time t and one asks for the probability $\psi(x, t)$ for a particle to be at a given spot at that time. In accordance with the common custom, one splits the total time t into small intervals τ; the progress of a particle during any interval τ is some random function and the summation of all infinitesimal 'progresses' yields the position of the particle at time t. If the mean progress during τ is $\bar{\xi}$, and if the deviation from $\bar{\xi}$ during τ is random, then the function $\psi(x, t)$ will be Gaussian, simply because of the central limit theorem of probability theory. It can be represented most easily in a system of coordinates $x't'$ in which $\int x'\psi(x', t)\, dx' = 0$, that is, in a system that moves with the 'mean' flow. The velocity v of the mean flow depends on the external conditions, such as pressure drop, as well as on properties of the porous medium and the fluid.

In the present case (Case A) the basic flow equation is therefore

$$\frac{\partial\psi}{\partial t'} = D\frac{\partial^2\psi}{\partial x'^2} \tag{1}$$

$$x = x' + vt' \tag{2a}$$

$$t = t' \tag{2b}$$

In the coordinates x, t this is

$$\frac{\partial \psi}{\partial t} = D \frac{\partial^2 \psi}{\partial x^2} - v \frac{\partial \psi}{\partial x} \tag{3}$$

Remember that v as well as D are constants in any one linear experiment where the conditions for the total flow are held steady; v and D, however, may depend on the pressure drop.

Case A corresponds essentially to a random-walk picture of flow through porous media. One can modify this idea somewhat by assuming that there is autocorrelation between subsequent time-steps. This case has been discussed by the author [*Scheidegger*, 1958a] and it was shown that, in the moving coordinate system (2) one ends up with a telegraph equation instead of with a diffusivity equation. This represents the Case B, thus

$$\frac{\partial \psi}{\partial t'} = D \frac{\partial^2 \psi}{\partial x'^2} - A \frac{\partial^2 \psi}{\partial t'^2} \tag{4}$$

In terms of x, t, this yields

$$\frac{\partial \psi}{\partial t} + v \frac{\partial \psi}{\partial x} = D \frac{\partial^2 \psi}{\partial x^2} - A \left[v^2 \frac{\partial^2 \psi}{\partial x^2} + 2v \frac{\partial^2 \psi}{\partial x \partial t} + \frac{\partial^2 \psi}{\partial t^2} \right] \tag{5}$$

Again, the quantities A, D, and v depend on the other dynamic parameters such as pressure drop, according to the microdynamic assumptions which are being made. In Case A as well as in Case B, one can therefore introduce a variety of assumptions and come up with a variety of models. However, if an 'overall steady state' be considered, that is, a state in which the total flow velocity is steady, then these various parameters are constants.

Progress of a slug—In order to evaluate the two models of miscible displacement, they must be compared with experiments. As stated in the introduction, two types of linear experiments can easily be performed. Starting with a very thin slug of tracer substance at $x = 0$, one can observe its spreading; similarly, starting with a sudden jump in concentration of tracer substance at $x = 0$, one can observe the flattening of the saturation drop.

We shall start with a consideration of the progress of a thin slug in the two cases. This requires that the fundamental differential equations pertaining to each of the two cases be solved for the initial condition.

$$\psi(x, 0) = m_0 \delta(x) \tag{6}$$

where δ denotes the Dirac delta function and m_0 (which we shall set equal to unity in the following lines) is the total amount of tracer substance contained in the slug. Then, ψ is a linear density (= amount/unit length) and therefore proportional to the concentration of tracer per unit length.

The solution for Case A is well known, since the basic equation is simply a diffusivity equation. It is [*Crank*, 1956]

$$\psi = \frac{1}{(4\pi D t)^{\frac{1}{2}}} \exp\left(-\frac{x'^2}{4Dt}\right) \tag{7}$$

with, as usual

$$x' = x - vt \tag{8}$$

v being the pore velocity of the total flow.

The shape of the curves representing $\psi(x)$, for various values of t, is shown in Figure 1.

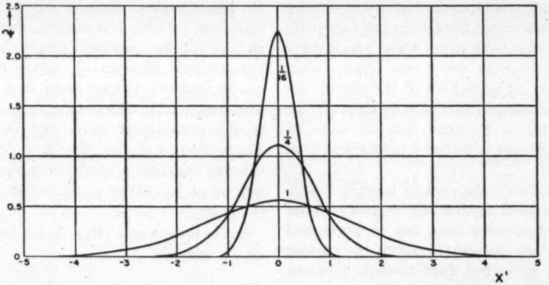

FIG. 1 – Shape of a slug of tagged fluid passing through a porous medium if no autocorrelation is taken into account

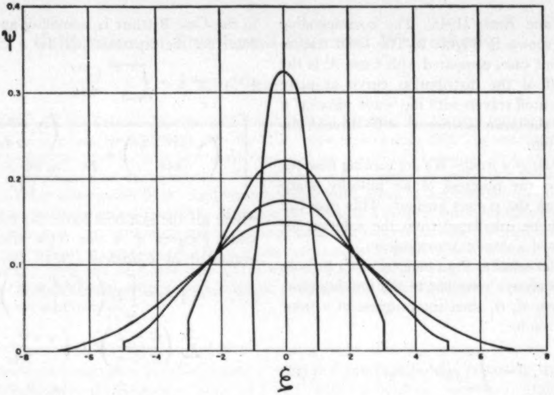

FIG. 2 – Shape of a slug of tagged fluid passing through a porous medium if autocorrelation is taken into account

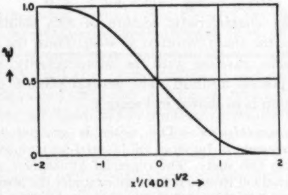

FIG. 3 – Shape of a concentration front during miscible displacement in a porous medium without autocorrelation

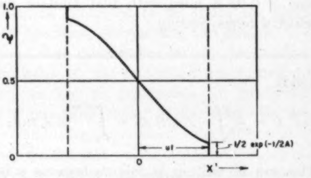

FIG. 4 – Shape of a concentration front during miscible displacement in a porous medium with autocorrelation

We turn next to Case B. In this instance, one has to solve the telegraph equation (4) for the boundary condition (6). The solution for this problem has been given by *Goldstein* [1951]. It is

$$\left.\begin{aligned} \psi(x', t) &= \frac{e^{-t/2A}}{4Au}\left[I_0(Y) + \frac{t}{2A}\frac{I_1(Y)}{Y}\right] \\ &\qquad\qquad \text{for } |x'| < ut \\ &= 0 \qquad\qquad \text{for } |x'| > ut \end{aligned}\right\} \tag{9}$$

with

$$Y = (u^2t^2 - x'^2)^{\frac{1}{2}}/(2Au) \tag{10}$$

$$D = Au^2; \qquad u = (D/A)^{\frac{1}{2}} \tag{11}$$

$$x' = x - vt \tag{12}$$

and I_0, I_1 are Bessel functions with imaginary argument

$$I_0(x) \equiv J_0(ix) = \sum_{m=0}^{\infty} \frac{(\frac{1}{2}x)^{2m}}{(m!)^2} \tag{13}$$

$$I_1(x) \equiv -iJ_1(ix) = \sum_{m=0}^{\infty} \frac{(\frac{1}{2}x)^{2m+1}}{m!(m+1)!} \tag{14}$$

In order to evaluate the above formulas, let us set

$$\xi = x'/(2Au) = x'/(2\sqrt{AD}) \tag{15}$$

and

$$\tau = t/(2A) \tag{16}$$

Then the solution becomes

$$\left.\begin{aligned} \psi(\xi, \tau) &= \tfrac{1}{2}e^{-\tau} \\ &\cdot\left[I_0(\sqrt{\tau^2 - \xi^2}) + \tau\frac{I_1(\sqrt{\tau^2 - \xi^2})}{\sqrt{\tau^2 - \xi^2}}\right] \\ &\qquad\qquad \text{for } \xi < \tau \\ &= 0 \qquad\qquad \text{for } \xi > \tau \end{aligned}\right\} \tag{17}$$

which is also properly normalized. The values of ψ have been calculated for a representative number of the arguments, using the tables of functions of *Jahnke* and *Emde* [1945]. The corresponding curves are shown in Figure 2. The chief feature of the present case, compared with Case A, is the sharp cutoff of the distribution curve at early times. The cutoff travels with the 'wave velocity' u (referred to the mean position $x' = 0$) through the porous medium.

The progress of a front—We are turning now our attention to the progress of an initially sharp front through the porous medium. This case can immediately be calculated from the solution for the progress of a slug by superposition.

Denote the solution for a slug by $\sigma(x', t)$ (note that we are always referring to the moving coordinate system x', t), then the progress of a front is simply given by

$$\psi(x', t) = \int_{-\infty}^{0} \sigma([x' - \zeta], t)\, d\zeta \qquad (18)$$

if originally (at $t = 0$) all space $x' < 0$ (this is also $x < 0$) is filled with that kind of fluid to which ψ refers. Setting

$$x' - \zeta = \eta \qquad (19)$$

yields

$$\psi(x', t) = -\int_{\infty}^{x'} \sigma(\eta, t)\, d\eta = \int_{\eta=x'}^{\eta=\infty} \sigma(\eta, t)\, d\eta \qquad (20)$$

This can be written as follows because σ is normalized and symmetrical with regard to $x' = 0$

$$\left.\begin{aligned} \psi(x', t) &= \tfrac{1}{2} - \int_{\eta=0}^{\eta=x'} \sigma(\eta, t)\, d\eta \quad \text{for} \quad x' > 0 \\ &= \tfrac{1}{2} + \int_{\eta=x'}^{\eta=0} \sigma(\eta, t)\, d\eta \quad \text{for} \quad x' < 0 \end{aligned}\right\} \qquad (21)$$

For the Case A this yields [*Crank*, 1956]

$$\begin{aligned} \psi(x', t) &= \tfrac{1}{2} - \int_0^{x'} \frac{1}{(4\pi D t)^{\frac{1}{2}}} \exp\left[\frac{-\eta^2}{4Dt}\right] d\eta \\ &= \tfrac{1}{2} - \int_0^{x'/\sqrt{4Dt}} \frac{1}{\sqrt{\pi}} e^{-z}\, dz \\ &= \tfrac{1}{2} - \tfrac{1}{2} \operatorname{erf} \frac{x'}{\sqrt{4Dt}} \end{aligned} \qquad (22)$$

where erf denotes the error function. The latter is well known; tables are available. The general appearance of the solution (22) is shown in Figure 3.

Finally, we investigate the progress of a front in the Case B (that is, assuming autocorrelation). Inserting the expression (9) for σ into (22) yields

$$\psi(x', t) = \tfrac{1}{2} - \int_{\eta=0}^{\eta=x'} \frac{e^{-t/2A}}{4Au} \cdot \left[I_0\left(\frac{\sqrt{u^2t^2 - \eta^2}}{2Au}\right) + \frac{t}{2A} \frac{I_1\left(\dfrac{\sqrt{u^2t^2 - \eta^2}}{2Au}\right)}{\dfrac{\sqrt{u^2t^2 - \eta^2}}{2Au}} \right] d\eta \qquad (23)$$

where all the symbols have the meaning defined under *Progress of a slug*. This integral has been evaluated by *Goldstein* [1951], the result is

$$\left.\begin{aligned} \psi(x', t) &= \tfrac{1}{2} e^{-t/2A} \left[I_0\left(\frac{\sqrt{u^2t^2 - x^2}}{2Au}\right) + 2\sum_{n=1}^{\infty} \left(\frac{ut - x'}{ut + x'}\right)^{\frac{\eta}{2}} I_n\left(\frac{\sqrt{u^2t^2 - x'^2}}{2Au}\right)\right] \\ &\qquad\qquad \text{for} \quad 0 < x' < ut \\ &= 0 \qquad\qquad \text{for} \quad x' > ut \end{aligned}\right\} \qquad (24)$$

and corresponding values for $x' < 0$.

The characteristic feature of this solution is again the sharp cutoff at $x' = ut$. Thus, the cutoff is again traveling with the 'wave velocity' u into the porous medium. The general picture of the solution is as shown in Figure 4.

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Calibration of Five Small Forested Watersheds

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Abstract—On the Fernow Experimental Forest in West Virginia, five forested watersheds, 38 to 96 acres in area, have been gaged by the U. S. Forest Service since 1951. The watersheds are close together, for the most part contiguous, and are similar in topography, soil, forest cover, and stream-flow characteristics. The methods and problems of calibration should interest other investigators in this field because seldom has a group of watersheds been calibrated for forest watershed research to determine the effects of a range of cutting treatments. After calibration, four watersheds will be cut over, using four different cutting practices. One watershed will be used as a control. Effects of treatment on stream flow will then be measured. Methods of Wilm and of Kovner and Evans were used to determine length of calibration period based on an analysis of annual, monthly, peak, and low flows. Problems of treatment assignment are discussed.

Introduction—The effect of different types of forest management on stream flow is being investigated by the Mountain State Research Center of the Northeastern Forest Experiment Station, U. S. Forest Service, on the Fernow Experimental Forest in Tucker County, near Parsons, W. Va.

Five forested watersheds, ranging from 38 to 96 acres in area, have been continuously gaged since May 1951 (Fig. 1; 80 chains = one mile). V-notch weirs (120°) and continuous water-stage recorders are used. Water quality, precipitation, and soil-moisture content are also being measured.

The watersheds, supporting a 50-year old stand of hardwood timber, have been undisturbed for several decades. Slopes are steep; soils are stony and for the most part shallow.

For calibration of these watersheds, a relationship was established between stream-flow measurements for a period of years in each watershed to be treated and concurrent measurements in another watershed, the control. An analysis was made testing the predictive value of the relationship, to determine (1) the standard error of estimate of the prediction, and (2) the number of observations after treatment required to establish the significance of a difference considered to be of practical importance.

Analytical methods for determining the adequacy of calibration of annual discharge from small watersheds have been presented by *Wilm* [1949] and by *Kovner* and *Evans* [1954]. In this paper application of these methods to peak flows and low flows as well as annual discharge is discussed.

After calibration, four of the Fernow watersheds will be cut over, each by a different system. These systems range from a commercial clearcut with skid roads at maximum operable grades to a conservative selection system (intensive forestry) with skid-road grades not exceeding ten per cent and with provisions for road drainage. One watershed will be left in its undisturbed state as a control. After treatment, stream-flow measurements will be continued to determine the effect on water quantity, distribution, and quality.

During the calibration period, stream-flow characteristics of one watershed are related to another, leading to expressions for predicting values of one from values of the other. We are using straight-line regressions after determining that they fit the data well. For example, based on five years of record, the equation $Y = 0.35 + 0.91X$ enables us with a certain degree of accuracy to predict the annual flow in area-inches of Watershed 1 (Y) from that of Watershed 3 (X).

Length of calibration period—One problem faced, as in all such experiments, was to determine the proper length of the calibration period based on acceptable error. Too short a calibration period would lead to inconclusive results. Too long a calibration period results in unnecessary expense. Our problem is complicated by the fact that the period for measurement of treatment effects will be of limited duration: after logging, the watersheds will recover and effects will diminish. We are thinking in terms of a period of two or three years during which effects of treatment will be at or near a maximum.

Kovner and Evans prepared a graphical solution of Wilm's equation for determing the minimum length of the calibration period. Modified to include a larger number of observations, their graph is reproduced in Figure 2. The horizontal axis shows the number of observations in the calibration period. The vertical axis is the squared ratio:

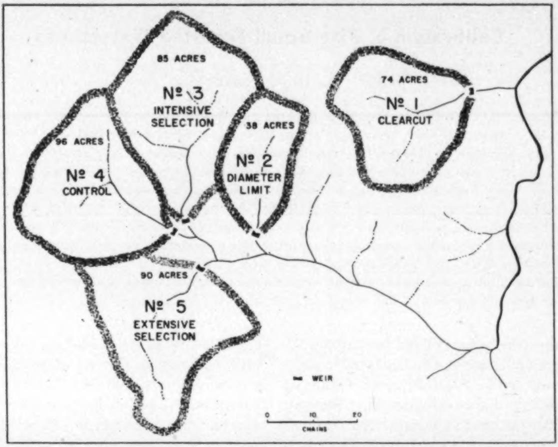

FIG. 1 – Locations of the five gaged watersheds on the Fernow Experimental Forest, showing proposed treatments

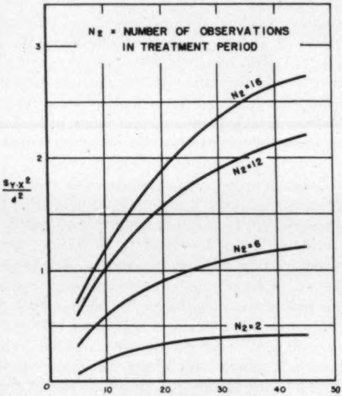

FIG. 2 – Graph for determining duration of calibration and treatment periods, revised from *Kovner* and *Evans* [1954]

standard error of estimate divided by the smallest worthwhile difference. The graph shows a family of curves. Given the number of observations in the calibration period and a value for $s_{y \cdot x}^2/d^2$, the number of observations needed in the treatment period can be read or interpolated.

To use this method, certain assumptions must be made. First, a value must be assigned for d, the smallest worthwhile difference. This might be the smallest difference expected as a result of treatment, based on experience, or a difference due to treatment of such a magnitude that if it is not reached the investigator is willing to forego determination of its significance. Another assumption made, and open to some question, is that variances after treatment will be of the same magnitude as those before treatment.

Analysis—Five years of data were analyzed as a basis for deciding the length of the calibration period and assignment of treatments to individual watersheds. Annual and monthly water flows, peak flows, and low flows were analyzed. Water quality was not analyzed because from previous studies at the Fernow Experimental Forest and elsewhere there seems little doubt that changes in quality, such as turbidity, that result from treatment will be significant.

Mean annual flow ranged from 20 to 27 area-inches for the five watersheds. Regression equations were computed to predict annual flow of each of the watersheds from each of the others; best predictions were obtained with Watershed 3 as the control.

TABLE 1 – *Calibration of four watersheds on Watershed 3; correlation coefficients and errors of estimate*

Item	Watershed							
	1		2		4		5	
	Cor. coef.	Error of est.	Cor. coef.	Error of est.	Cor. coef.	Error of est.	Cor. coef.	Error of est.
Annual flow (error of estimate in area inches)	0.99993	0.055	0.995	0.592	0.996	0.493	0.9988	0.326
Peak flow (error of estimate in csm[a])	0.984	3.72	0.990	3.67	0.990	2.42	0.975	4.86
Low flow (error of estimate in number of days flow less than 0.05 csm[a])	0.998	3.92	0.995	5.35	0.997	4.32	0.995	5.03

[a] Cubic feet per second per square mile.

For the four regressions predicting flow from Watershed 3, the errors of estimate ranged from 0.05 to 0.59 area-inch of water (Table 1). Correlation coefficients ranged from 0.995 to 0.99993. Using the procedure described, with five years in the calibration period and Watershed 3 as the control, one or two years would be required in the treatment period of each of the other watersheds to establish significance at the five per-cent level of a ten percent change in flow of the treated watershed (Table 2). We will be willing to forego determination of its statistical significance if change in flow is less than ten per cent.

With five years of record, there are of course only five observations of annual flow for each watershed, a small number for regression analysis. Therefore, consideration was given to analyzing monthly flows, giving 60 observations in five years. Analysis similar to that already given indicated that, with Watershed 3 as the control, only two to six months would be required to establish significance of a ten per-cent change at the five per-cent level. However, there are objections, often referred to as 'serial correlation', to use of monthly data in this way. For this reason reliance was not placed upon analysis of data by months.

TABLE 2 – *Calibration of four watersheds on Watershed 3; years required in treatment period with calibration period of five years*

Item	Smallest worthwhile difference	Watershed			
		1	2	4	5
	pct	yr	yr	yr	yr
Annual flow	10	1	2	2	1
Peak flow[a]	10	2 (14)	2 (11)	1 (7)	2 (16)
Low flow	20	2	3	2	4

[a] Years required based on average occurrence of peaks in calibration period. Required number of observations (peaks) given in parentheses.

TABLE 3 – *Calibration of four watersheds on Watershed 4; years required in treatment period with calibration period of five years*

Item	Smallest worthwhile difference	Watershed			
		1	2	3	5
	pct	yr	yr	yr	yr
Annual flow	10	2	3	2	1
Peak flow	10	3 (25)	2 (19)	1 (8)	3 (24)
Low flow	20	1	3	3	3

Basic data used in the peak-flow analysis were the peaks at each watershed on 45 occasions when flow of Watershed 3 exceeded ten cu ft/sec mi^2. Peak flows ranged up to 180 cu ft/sec mi^2 and averaged between 21 and 29 cu ft/sec mi^2 for the five watersheds. Regressions were computed to estimate peaks of each watershed from peaks of each of the others. With Watershed 3 as the control, analysis indicates that seven to 16 peaks would be required in the treatment period to establish the significance (at five per-cent level) of a ten per-cent change due to treatment. In the calibration period, there was an annual average of nine peaks of the size included in the analysis. Thus the required treatment period might be about two years.

More difficulties were encountered in the analysis for low flows than in the others. First, it was difficult to decide upon a good measure of low flows. After trial runs using several different approaches, analysis was based upon number of days in the year when flow was 0.05 cu ft/sec mi^2 or lower. For the five years on five watersheds, number of such days varied from 3 to 166. Analysis indicates that, with Watershed 3 as the control, two to four years in the treatment period will be required to establish the significance at the five per-cent level of a 20-pct change in number of days. We are still trying to find a better measure for low flows.

Decisions made—Based on the analysis, we decided to wait until one additional year of record, making six in all, has been obtained before starting treatment. The measurement of low flows gives the most concern. However, results of experiments elsewhere indicate the probability that the effect of treatment on low flows may be greater proportionally than for annual flows.

For several reasons, treatments assigned to individual watersheds were not at random. This made our statistician advisors uneasy, but they finally agreed. Watershed 3 was originally chosen as the control because generally it gave the highest correlations; Watershed 4, well correlated with Watershed 3, was designated for the intensive forestry practice, the least drastic treatment.

However, a proper road for the intensive practice could not practicably be constructed in Watershed 4 without crossing into Watershed 3. Therefore, Watershed 4 was made the control, and Watershed 3 was assigned the intensive forestry practice since a road could be built into Watershed 3 without infringing upon adjacent watersheds. (Table 3 shows years required in treatment period with Watershed 4 as the control). Watershed 1 was chosen for clear-cutting, a destructive practice, for the compelling though unscientific reason that of all five watersheds it is the only one situated below the reservoir of the nearby town of Parsons. Watershed 1 was well correlated with Watershed 4. Thus, the two extremes of treatment were assigned to the watersheds best correlated with the control. The intermediate treatments, a diameter-limit cut and extensive forestry, were assigned to Watersheds 2 and 5.

Conclusions—Five years of record showed remarkably good correlation in stream-flow characteristics of the five gaged watersheds. The methods of Wilm, and Kovner and Evans proved suitable for the analysis of data in this experiment and led to an apparently sound evaluation of necessary length of calibration period. A final evaluation of the methods used cannot be made, of course, until after the treatment period.

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A Note on the Dispersion of a Salt-Water Boundary Moving through Saturated Sand

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Abstract—Theoretical aspects on this problem are presented referring in particular to a recent work by *Day* [1956]. The theoretical approach by Day is criticized because it involves a time-dependent dispersion function in a stationary flow. It is pointed out that the dispersion in an isotropic medium should be limited and depend only on the soil material whereas in an anisotropic medium the dispersion is expected to depend also on the length of travel of the front.

In a recent paper in this journal, *Day* [1956] discusses the dispersive effects that can be noted in an advancing salt-water boundary moving through saturated sand. As this phenomenon cannot be explained by simple molecular diffusion it is of considerable theoretical interest apart from its practical consequences. To distinguish it from molecular mixing the name longitudinal mixing has been proposed, and at least during short time intervals, its effect far exceeds that of molecular diffusion.

The longitudinal mixing has, as Day points out, been known for some time and has been studied to some extent recently by *Kaufman* and *Orlob* [1956] in a work on the possible use of tracers for studying ground-water flow rates. The explanation of the phenomenon generally accepted is that on a microscale the velocity distribution along true streamlines of a laminar flow through porous soil must be highly variable depending upon how close to particle surfaces the streamlines run. Day accepts this explanation but assumes also that the average velocity along a streamline differs from the bulk velocity, referring to the conditions in a capillary tube. He progresses by applying statistical reasoning and arrives at the conclusion that the dispersion of a moving salt-water front can be described by the common diffusion equation, $\partial C/\partial t = D\nabla^2 C$, where C is the bulk concentration and D is the factor of dispersion and has the same dimension as a diffusion coefficient. His experimental data also fit a solution to this differential equation which, however, is no proof that the differential equation has any physical significance in the case considered. It merely indicates that the dispersion of the front can be described by an integrated probability function of bulk concentration. There is a strong reason to suspect that the differential equation used by Day is improper because it is a function of time. The streamline pattern in laminar flow is fixed by the geometry of the arrangement of pores through which the flow takes place and should be independent on the rate of flow as long as the flow is laminar. The longitudinal mixing should therefore not be a function of time but, if any, of the distance of flow. Hence, the factor of dispersion D in the differential equation can have no physical meaning as it will depend on the average rate of flow. This is actually demonstrated by the experimental data Day refers to as will be seen in the following.

As the data fit an integrated probability function it is obviously possible to relate the standard deviation σ of this probability function to the factor of dispersion D by $\sigma = \sqrt{2Dt}$. In the first experiment at a flow rate of 1.811 cm min^{-1} Day finds that D must be 0.02 cm^2 min^{-1} to fit the observed dispersion of the front. In the second experiment the flow rate was 0.626 cm min^{-1} and the calculated $D = 0.080$ cm^2 min^{-1}. As the distance of flow in both experiments was 26 cm it is possible from these data to calculate $\sigma = \sqrt{2Dt}$ and it becomes 2.40 cm in the first experiment and 2.58 cm in the second, thus practically the same. Obviously only σ, which can be called the characteristic dispersion, has any physical meaning in this case as it represents a constant that presumably is related to the particle size. This is at least implied by its dimension.

The basic assumption made by Day that the average velocity along a streamline differs from the bulk velocity has not been verified in his experiments. It can be proved only by determining the characteristic dispersion σ for different distances of flow.

Before discussing the physical interpretation of σ further, the question about the velocity distribution along true streamlines in laminar flow should be taken up. In the case of flow in a capillary tube the picture of the flow is simple, and it can be inferred that the dispersion must increase with the distance of flow as Day also inferred. It should be noted, however, that if flow took place in such capillaries it would represent a highly anisotropic medium as permeability in any other direction is zero. In a soil particles will be more or less randomly arranged and consequently also the pores through which water flows. In the extreme case one could imagine a completely random arrangement of pores and consequently a completely isotropic permeable material. There would be no favored paths for the streamlines as the pores are branching in any direction in a random manner. Following a streamline one would expect it to go sometimes in the center of a pore, sometimes close to a particle surface but most of the time in any position between these two extremes. The average velocity along any streamline can be expected to be the same as the bulk velocity. The distance s traveled along a streamline can be related to the time and velocity by $ds = v\,dt$ so the average velocity between two points s_1 and s_2 along the streamline can be formulated

$$\bar{v} = \int_{s_1}^{s_2} ds \Big/ \int_{s_1}^{s_2} ds/v$$

If $\bar{v}$ becomes practically constant for a finite distance $\Delta s = s_2 - s_1$ and equal to the bulk velocity, the quantity Δs can be related to the characteristic dispersion σ discussed earlier. One would expect that in the extreme case for $\Delta s = 6\sigma$, $\bar{v}$ would be equal to the bulk velocity but in most cases a smaller distance is required. This is the physical interpretation of σ in the isotropic case. The diffuse front can be pictured as being derived from the originally plane front by needle-like deformations in the direction of flow, the deformations being due to different velocities. The deformation is, however, kept within a certain width 6σ all the time though the topography changes with the flow. The originally plane front can be regarded as a highly improbable case of this ever-changing surface.

If $\bar{v}$ in the formula above should attain a value different from the bulk velocity, which would happen in an anisotropic medium, things become more complicated as then the distribution of average velocities enters the picture. One would expect that for short distances of flow the integrated probability function should well picture the deformation of the front, but for long distances of flow the distribution of average velocities would dominate giving a different picture of the front, maybe something like that for a capillary tube. So there are apparently two basically different processes that can cause longitudinal mixing. Unfortunately, the effect of one cannot be simply superimposed on the effect of the other as one process is dispersive in nature and the other advective.

For the dispersive process one would expect a linear relation between σ and the particle size d. The soil material used by Day had most of the particles in the size range 1–2 mm or say 0.15 cm as an average. Writing $\Delta s = 6\sigma = kd$ where d is the particle diameter, it is seen, using $\sigma = 2.5$ cm that k becomes 100. Due to overlapping of particles when projected one would expect that for a distance 6σ a streamline has to pass about 150 particles. This means that in the most extreme cases the average velocity along a streamline is reached after passing about 150 particles but more frequently after passing a smaller number.

The longitudinal mixing discussed above concern small scales but a similar reasoning can apparently be applied to larger scales where stratification of the soil material causes variations in the average flows discussed above. Not only stratification of soil material can contribute but also structural elements found in soils as results of soil-forming processes. On a larger scale the dispersive effects will also be larger as demonstrated by the field experiments by *Kaufman* and *Orlob* [1956]. There is thus a formal resemblance between dispersive forces in ground-water flow and in the atmosphere, namely that they are proportional to the scale considered.

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A Note on the Differential Equation of Steady, Gradually Non-Uniform Flow in Open Channels

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Abstract—This note is intended to clarify the sign convention used in the derivation of the differential equation for steady, gradually non-uniform flow in open channels. This clarification is accomplished through the proper use of the reference axis. Such an equation is known to have special forms for various channel shapes. Equations for both the prismatic and non-prismatic channel are summarized.

Non-uniform flow may best be defined by first explaining uniform flow. Uniform flow in an open channel can be established if the channel has the following characteristics: relatively long, of uniform roughness, and geometrically prismatic, that is, a constant slope, alignment, and cross section. Under such conditions, a steady, gravitational flow will have a uniform depth. Therefore the flow area and the mean velocity will remain constant along the flow direction. The energy slope S_e, the water-surface slope S_w, and the bottom slope S_0 have the same value.

In the case where the characteristics of a channel are not as stated above, uniform flow is no longer possible. The flow is then called non-uniform. The conditions necessary for uniform flow to exist are quite severe. The flow in most waterways is not uniform. The following discussion is limited to the case of gradually non-uniform flow, that is, the non-uniformity of the flow is appreciable over a relatively long distance.

The differential equation for steady, gradually non-uniform flow in open channels has been reported in various forms in books of hydraulics [*Rouse*, 1950, p. 610]. Students of hydraulics have found some difficulty in understanding the derivation of such an equation. The difficulty is mainly from two sources: (1) the sign convention for the channel slope, and (2) the sign convention for the energy gradient. The purpose of this discussion is to clarify the derivation by using a simplified sign convention.

The total energy per unit weight of a flow with a uniform velocity V can be written as (see Fig. 1, the channel has a moderate slope)

$$E = V^2/2g + y + z \tag{1}$$

both E and z are measured upward from the datum, y is measured from the stream bed, $V^2/2g$ is measured upward from the water surface. It should be noted that: (a) For real fluid, the total energy E always decreases along the flow direction. A positive energy gradient means that the energy increases toward upstream. If l is positive toward upstream, $dE/dl = S_e$. (b) The channel slope is customarily defined as positive in the case where the bed elevation decreases in the downstream direction, that is, the slope is positive if the elevation of the channel bottom increases in the upstream direction, $dz/dl = S_0$. Differentiate E with respect to l

$$\frac{dE}{dl} = \frac{d}{dl}\left(\frac{V^2}{2g}\right) + \frac{dy}{dl} + \frac{dz}{dl} \tag{2}$$

therefore

$$S_e = \frac{d}{dl}\left(\frac{V^2}{2g}\right) + \frac{dy}{dl} + S_0 \tag{3}$$

If (2) is multiplied by minus one

$$\frac{dE}{d(-l)} = \frac{d}{d(-l)}\frac{V^2}{2g} + \frac{dy}{d(-l)} + \frac{dz}{d(-l)} \tag{4}$$

Eq. (3) becomes

$$-S_e = \frac{d}{d(-l)}\frac{V^2}{2g} + \frac{dy}{d(-l)} - S_0 \tag{5}$$

denoting $-l$ by x, we have

$$\frac{dE}{dx} = \frac{d}{dx}\frac{V^2}{2g} + \frac{dy}{dx} + \frac{dz}{dx} \tag{6}$$

$$-S_e = \frac{d}{dx}\frac{V^2}{2g} + \frac{dy}{dx} - S_0 \tag{7}$$

Eq. (7) is the dynamic equation for open channel flow. (According to *Iwagaki* [1953, p. 7], (7) is a special case of the dynamic equation for real fluid flow and should be derived directly from the Navier-Stokes equation.) It can be obtained directly by differentiating (1) with respect to x. Note that

$$\frac{dE}{dx} = -Se \text{ and } \frac{dz}{dx} = -S_0 \tag{8}$$

Eq. (8) means that both the total energy head and

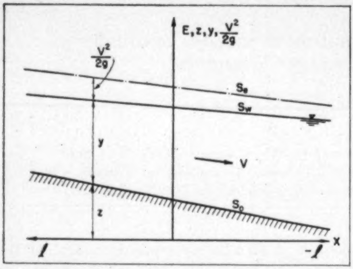

FIG. 1 – Definition sketch for gradually, non-uniform flow

the bottom elevation decrease in the flow direction.

If the channel is prismatic, the velocity head is only a function of the flow depth for a given discharge

$$\frac{d}{dx}\left(\frac{V^2}{2g}\right) = -\frac{Q^2}{gA^3}\frac{dA}{dx} = -\frac{Q^2B}{gA^3}\frac{dy}{dx} \tag{9}$$

Substituting (9) in (7) yields [*Rouse*, 1950, p. 610]

$$\frac{dy}{dx} = \frac{S_0 - S_e}{1 - Q^2B/gA^3} \tag{10}$$

where B is the water-surface width, A is the flow area, and Q is the total discharge.

If the channel is not prismatic, for a given discharge (steady flow) the velocity head is a function of the flow depth, and the distance x. For example, if the channel has a rectangular cross section, and its width B is a function of x, $A = By$

$$\frac{dA}{dx} = \frac{d}{dx}(By) = B\frac{d}{dx}y + \frac{dB}{dx}y \tag{11}$$

Substituting (11) in (7), and letting $Q^2/gB^2 = y_c^3$, yield [*Homma*, 1952, p. 158]

$$S_0 - S_e = \left[1 - \left(\frac{y_c}{y}\right)^3\right]\frac{dy}{dx} - \left(\frac{y_c}{y}\right)^3\frac{y}{B}\frac{dB}{dx} \tag{12}$$

Eq. (12) is the general equation for steady, gradually non-uniform flow in a rectangular channel of varying width.

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Preliminary Report on the Alaskan Earthquake of April 7, 1958

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Abstract—The Alaskan earthquake of 05h 30m April 7, 1958 (150° WMT) is the largest (Richter scale 7.0–7.5) of a series of shocks centered in an area near Huslia, Alaska. Severe breakage of lake and river ice and many ground cracks and mud flows occurred in the region of the field epicenter. A preliminary isoseismal map is presented.

The major Alaskan earthquake of 05h 30m April 7, 1958, 150° West Meridian Time, was felt sufficiently strong in Fairbanks to awaken many persons. The shock, of Richter magnitude 7.0 to 7.5, disaligned magnetic instruments of the U. S. Coast and Geodetic Survey Observatory at College, and was recorded on magnetic instruments at various field stations in Alaska. The intensity of the preliminary waves was sufficient to obscure the arrival of the secondary waves on the seismic equipment at the U. S. Coast and Geodetic Observatory at College. Through the use of S-P times of aftershocks, data from Sitka and other more distant stations it was possible to establish the epicenter as being about 250 mi northwest of Fairbanks.

On April 10, the author was flown to the area and was able to establish the field epicenter at a point near Huslia, Alaska, in the Koyukuk River basin. The position of the field epicenter is 155° 30′W, 65° 45′N. Severe lake-ice cracking, ground cracks, sinks, and extensive mud flows occurred in a zone approximately three miles wide by 35 miles long (Fig. 1) extending from the village of Huslia on the Koyukuk River in a northeasterly direction (azimuth 75° true) to a second point on the Koyukuk River. The southern part of the general area suffering the most severe surface effects consists of Quaternary alluvium and the northern part intersects a Tertiary volcanic ridge known as Bear Mountain.

At the time of the earthquake there was about two feet of snow on the ground and all lakes and rivers were frozen to a depth of approximately three feet. These conditions aided greatly in locating the area most affected by the shock.

The only nearby inhabitants of the region live in Huslia, a village of 150 people. The residents reported the duration of strong shaking to be approximately one minute, with horizontal motion SW-NE most noticeable. The shocks or preliminary earth noises at about 05h 30m 150° WMT awakened every adult in the village and caused some terror, particularly among the children. A moderate foreshock was felt by the villagers a week prior to the main shock at 05h 50m on March 31, 1958, 150° WMT and many aftershocks were also reported.

Actual monetary damage in Huslia was slight because most of the homes are of log construction and have no foundations. The only concrete found in the village was in piers underneath the one-story plywood school building. These were chipped by the main shock and some boards around the foundation of this building were knocked loose. Logs shook loose from window casings on two of the buildings and many of the houses received minor damage to roof structure. Case goods and other heavy objects moved for a distance of as much as twelve inches in the direction away from the epicenter.

Severe cracking of the river ice necessitated relocation of the river airstrip to a point where less cracking had occurred. Movement of the river ice created a pressure ridge of broken ice six feet in height along the southeast shore. Earth lurches on this bank left cracks in the soil up to forty inches wide and at least 20 ft deep.

Numerous earth lurches border small sloughs and ponds near Huslia. This area also contains a number of small mud flows and several sinks, some of which are 20 ft across and six feet deep. However, the most extensive damage is in an area between 10 and 30 mi northeast of Huslia. Many of the lakes in this region have large cracks in the ice with mud and vegetation ejected through them. Some lakes show severe shattering of the ice and in others no ice is visible. In these latter lakes, mud or muddy water appears to cover the ice completely. A few of the frozen streams had water or mud flowing in them after the shock.

The most striking result of the earthquake is the great volume of mud appearing on the surface at the field epicenter. Several of the larger mud flows cover an average area of one-quarter to one-half square mile with a mud depth of up to several

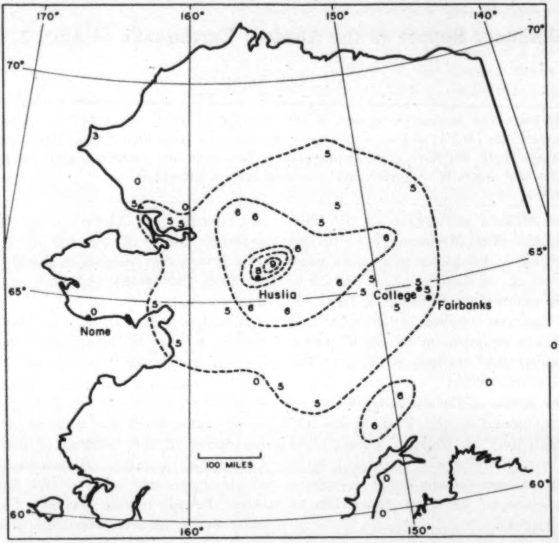

FIG. 1 – Preliminary isoseismal map of the earthquake of April 7, 1958

feet. One of the larger flows created a fanlike formation about 1000 ft long beyond which the mud flowed down a streambed for several miles. There are about ten flows of this size and hundreds of smaller ones. Associated with many of the flows are sinks located within a few hundred feet of the mud sources. The largest sink observed is 106 ft by 74 ft with a maximum depth of 13 ft.

As a part of the investigation of the earthquake a number of simplified questionnaires based on the U. S. Coast and Geodetic Survey earthquake questionnaire were sent to residents in Alaska. The response has been very good and a large amount of information is being obtained from the questionnaires and from voluntary letters. It is difficult to evaluate these data on the standard intensity scales because of the lack of a variety of construction near to the epicenter. Preliminary results indicate that the area over which the main shock was felt with an intensity of V or greater on the Modified Mercalli scale is in excess of 100,000 sq mi. As the shock occurred at a time when most people were asleep, the criterion of whether or not people were awakened was heavily used. The value V was assigned to a location if many or all persons were awakened by the shock. VI was assigned if most or all were awakened and if heavy objects were moved. At Huslia sand and mud ejection was the primary reason for the assignment of VIII. Preliminary intensity assignments at locations are shown on the accompanying map.

Subsequent to the earthquake vertical aerial photographs were taken which show the detail of the mud flows and ice cracking. One field party has visited the area and a second is planned. The results of these investigations will be published in a later paper.

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Compressibility and Temperature of the Earth's Interior

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Abstract—With a few assumptions regarding the constitution of the Earth's mantle and core, and using the values of pressure, density, and compressibility given by Bullen, the melting points at various depths were derived by Uffen's method. Assuming for the liquid core an adiabatic gradient, it seems that in the adopted Earth model the temperature of the lower mantle (below 800 km depth) is close to the melting point of the respective material and its strength is therefore much reduced. On the contrary the temperature of the upper mantle (depths 200 to 600 km) is considerably below the melting point and the material certainly has enough strength to permit the strain accumulation necessary to produce plutonic earthquakes.

Introduction—The temperatures of the interior of the Earth have attracted for a long time the attention of geophysicists. In recent years, *Uffen* [1952], *Jacobs* [1954], and *Verhoogen* [1954] have put forward important contributions to the problem. Their investigations assume, however, a homogeneous Earth's mantle, which appears to be a somewhat doubtful point [*Birch*, 1954]. In the present paper the non-homogeneity of the mantle will be also investigated, as well as its consequences regarding the temperature gradient within the Earth.

Effect of pressure on compressibility—*Bullen* [1953, pp. 220, 222] indicates the values of the bulk modulus $1/\chi$ and pressure P at various depths of the Earth (see Table 1), thus permitting to represent in Figure 1 the compressibility χ as a function of P. These adiabatic values of χ refer to the actual temperatures of mantle and core, where a temperature gradient certainly exists. Therefore the relations expressed in Figure 1 will also correspond to that gradient.

The variation of the compressibility is very regular within each of the regions B, D, and E (of Bullen's classification) and may be represented by the expression

$$\chi = a - bP + cP^2 \qquad (1)$$

where a, b, and c are coefficients which may depend on temperature. A least-squares adjustment gives for the coefficients the values indicated in Table 2, to which correspond the curves shown in Figure 1. The fit is extremely good.

For a homogeneous material at constant entropy the adiabatic compressibility is given by $\chi = (1/\rho)\, d\rho/dP$ where ρ is the density. By integration we obtain

$$\ln(\rho/\rho_0) = \int_0^P \chi\, dP \qquad (2)$$

from which ρ_0 (density at zero pressure) may be calculated.

We may use the compressibilities given by (1), but the values of ρ_0 must, in that case, correspond to the material that would exist at the level of zero pressure by imagining that the homogeneous layer and its temperature gradient were continued upward until that level.

Then by (1) and (2) we get

$$\ln(\rho/\rho_0) = aP - bP^2/2 + cP^3/3$$

Within each of the regions B, D, and E we can now compute the values ρ_0 corresponding to the values of ρ indicated in Table 1; the results are shown in Figure 2. Each of the three regions seems to be completely homogeneous but a considerable density difference exists between the upper and the lower mantle. This depends, however, on Bullen's assumptions for computing the densities, as was already pointed out by *Birch* [1952]. The values ρ_0 of each region correspond to a constant temperature which, as we shall see later, are incidentally not far from the respective melting point (about 1700 to 1900°K). Compressibilities at zero pressure, $\chi_0 = a$, evidently correspond to these same temperatures. Values of ρ_0 and χ_0 are given in Table 3.

It is almost generally accepted that the material in region B is some kind of dunite, and that the region E is composed of liquid meteoritic nickel-iron. The nature of the lower mantle (region D) is more uncertain. A reasonable fit to the value of the density is obtained if we assume a mixture of about equal parts of magnetite and olivine. At low pressure and low temperature χ is 0.5×10^{-12} cm²/dyne for magnetite, and 0.8×10^{-12} cm²/dyne for olivine [*Birch* and others, 1954]. We do not know however if at high temperature the compressibility of the mixture of the two minerals would decrease to only 0.4 × 10^{-12} cm^2/dyne (value in region D).

Another possibility, suggested by the stony meteorites, would be a rock formed by three parts olivine and one part meteoritic iron, but we know also too little about the behavior of such a mixture. It is interesting to remember that large concentrations of both magnetite and iron occur in a few places as segregations of igneous rocks [*Daly*, 1933, pp. 410, 559].

Melting point gradients—According to *Uffen* [1952] the melting point (in degrees Kelvin) of a solid may be computed by the simple formula

$$\tau = C/\rho\chi \tag{3}$$

where C is constant for a given material.

TABLE 1 – *Bullen's values of pressure, compressibility, and density*

Depth	P	χ	ρ
km	10^{12} dynes/cm²	10^{-12} cm²/dyne	gm/cm³
33	0.009	0.862	3.32
100	0.031	0.806	3.38
200	0.065	0.725	3.47
300	0.100	0.649	3.55
413	0.141	0.578	3.64
600	0.213	0.389	4.13
800	0.300	0.313	4.49
1000	0.392	0.279	4.68
1400	0.58	0.238	4.92
1800	0.78	0.205	5.14
2200	0.99	0.180	5.34
2600	1.20	0.161	5.54
2898	1.37	0.154	5.69
2898		0.161	9.4
3000	1.47	0.154	9.6
3500	1.95	0.123	10.2
4000	2.40	0.103	10.7
4500	2.81	0.090	11.2
4982	3.17	0.079	11.5

The formula is partly based on Lindemann's theory of fusion [*Richtmyer* and *Kennard*, 1947, p. 430], according to which ρ and χ (or the related frequency) must correspond to the solid phase at melting temperature. The actual temperature at the inner core boundary (depth about 5000 km) probably coincides with the melting point [*Jacobs*, 1956]. Near the base of the crust the melting point must also be reached because magmas are produced there; *Gutenberg* [1948] obtained evidence that this fact probably occurs at a depth of 80 to 100 km.

It is then reasonable to assume that between the depths of 100 and 5000 km the actual temperatures are never so far from the melting points that we might not compute these with Bullen's values of ρ and χ (and also with the values at zero pressure of Table 3).

From (3) we derive

$$\tau/\tau_0 = \rho_0\chi_0/\rho\chi \tag{4}$$

the subscript zero referring to the values at zero pressure.

The application of (4) to the upper core meets with some difficulty because there the material is assumed to be in the liquid state. As we are however calculating ratios of quantities affected by similar errors, the final result will not be much modified. In Table 4 we give the ratios τ/τ_0 computed by (4) for regions B, D, and E.

We shall now assume, for our Earth model, the following melting temperatures at zero pressure [derived from *Birch* and others, 1954; *Daly*, 1933]:

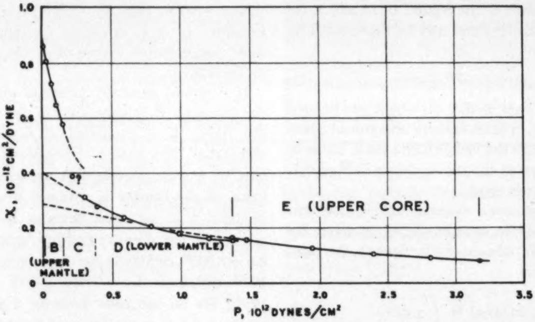

FIG. 1 – Compressibility as a function of pressure

TABLE 2 - *Coefficients of* $\chi = a - bP + cP^2$

Region	a	b	c
	10^{-12} cm²/dyne	10^{-24} cm⁴/dyne²	10^{-36} cm⁶/dyne³
B (upper mantle)	0.887	2.76	4.00
D (lower mantle)	0.400	0.344	0.120
E (upper core)	0.287	0.113	0.0150

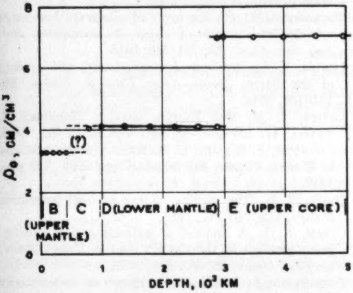

FIG. 2 - Zero pressure densities at various depths

TABLE 3 - *Values of* ρ_0 *and* χ_0

Region	ρ_0	χ_0
	gm/cm³	10^{-12} cm²/dyne
B (upper mantle)	3.29	0.887
D (lower mantle)	4.10	0.400
E (upper core)	7.0	0.287

TABLE 4 - *Melting points at various depths*

Depth	τ/τ_0	τ
km		10³ deg. K
33	1.02	1.7
100	1.07	1.8
200	1.16	1.9
300	1.27	2.1
413	1.39	2.3
800	(1.17)	(2.2)
1000	1.26	2.3
1400	1.40	2.6
1800	1.56	2.9
2200	1.71	3.2
2600	1.84	3.4
2898	1.87	3.5
2898	1.33	2.35
3000	1.36	2.4
3500	1.60	2.8
4000	1.82	3.2
4500	1.99	3.5
4982	2.21	3.9

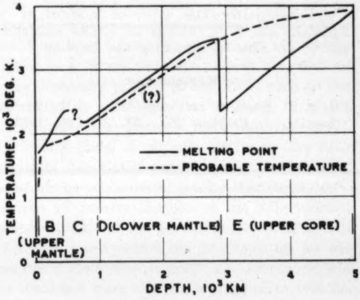

FIG. 3 - Melting points and probable temperatures within the assumed Earth model

upper mantle (dunite), 1670°K; lower mantle (magnetite?), 1860°K(?); upper core (nickel-iron), 1770°K. (For the composition of the lower mantle we assumed a mixture of minerals where the melting point of magnetite is probably representative of the melting point of the mixture.) The corresponding values of τ at the various depths are also given in Table 4.

At the boundary of the inner core the melting temperature is about 3900°K, which is close to that obtained by *Simon* [1953], but considerably below the values of *Gilvarry* [1956]. However, the same agreement with Simon's formula is not verified for the higher levels of the core, probably because there the temperature is a little too far from the melting point.

For the lower mantle and core the melting gradient (Fig. 3) has the general form suggested by *Jacobs* [1954]; but for the transition (region C) between the upper and lower mantle the decrease of the melting point (with increasing depth) is rather different from the usually assumed gradient.

Approximate temperatures—We have seen that temperatures at the depths of 100 and 5000 km may be assumed to coincide with the melting points for which we found 1800 and 3900°K, respectively. Transfer of heat in the liquid core (between the 5000 km level and the core boundary) must be partly due to convection, and therefore the adiabatic temperature gradient probably will be found in region E. A mean value of this gradient is 0.2 deg/km [*Jacobs*, 1956] and the temperature decrease, from 5000 to 2900 km, may be estimated at about 400°K, putting the temperature of the bottom of the mantle at 3500°K, which is a value of the order of magnitude of the melting point computed in the last chapter.

From the transmission of seismic waves we know that the mantle is in a solid condition, and then the temperature through the lower mantle must be somewhat below (but probably close to) the respective melting point (Fig. 3). At a depth of about 800 km a transition in the melting gradient is met and the material above this level appears to be a few hundred degrees below the melting point, until of course the depth of 100 km is approached.

Production of earthquakes depends on strain accumulation which is only possible if the material involved has enough strength. When the temperature of a solid is near the melting point, its strength is certainly very low, which is a condition found in the lower mantle of the assumed Earth model. This would explain why plutonic earthquakes only occur in regions B and C, no foci having been located at depths below 800 km.

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The Nature of the Mohorovicic Discontinuity

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Abstract—New evidence for the composition of the silicate mantle of the primary meteorite body suggests that a considerable portion of the Earth's upper mantle may well be composed of silicate material of basaltic composition. Consequently the Mohorovicic discontinuity may not separate basaltic crustal material from ultrabasic upper-mantle material but rather mark a zone in which basaltic material is transforming into a high-pressure modification possibly represented by the rock-type eclogite. Estimates of the temperatures and pressures at the average levels of the Mohorovicic discontinuity under oceans and continents give two points on the 'equilibrium line' for the transformation basalt → eclogite which is roughly given by the relationship $p = 21.8\theta - 488$ (p in bars, θ in °C). The geophysical consequences of this hypothesis are far reaching. It removes difficulties arising from the observed equivalence of oceanic and continental heat flows, provides satisfactory 'parent magma' from which the granitic and basaltic zones in the crust have differentiated, and suggests a mechanism for elevating or depressing regions of the Earth's surface simply by increasing or decreasing the temperature at the level of the Mohorovicic discontinuity beneath that region.

Introduction—The existence and depth of the Mohorovicic discontinuity which marks the accepted boundary between the Earth's crust and mantle are no longer in doubt. In general, geophysicists would agree that the composition of the 'continental' crustal rock is essentially that of an igneous rock intermediate between granite (or the even more petrologically likely rock-type granodiorite) and basalt while 'oceanic' crustal rocks are more likely to be basaltic in composition. On the other hand there is little agreement on the nature of the material which underlies the crust in both oceanic and continental regions.

Most workers have followed the concept that a change in chemical composition of the materials above and below the Mohorovicic discontinuity is the cause of the seismic discontinuity. For example in a recent review *Jacobs* [1956] concluded that peridotite best met the geophysical and geochemical requirements for the rock of the upper mantle while other authors, including *Bullen* [1953], have suggested dunite. From the literature it is obvious that these suggestions have been strongly influenced by Earth models proposed by *Washington* [1925] and others which were based on the then-existing knowledge of the compositions of the stony (that is, silicate rich) meteorites.

Evidence for a phase transformation—It is generally accepted that stony meteorites may be regarded as samples of the silicate mantle of the parent meteorite body and, by analogy, as samples of the chemical types of rock which probably make up the Earth's mantle. Previous models for the composition of the mantle of the parent meteorite body and the Earth have been confused by including the chondritic and polymict brecciated stony meteorites [for example, *Washington*, 1925; *Daly*, 1943; *Brown* and *Patterson*, 1948]. These are essentially tuffaceous and brecciated bodies which could not have formed by any process of differentiation of a silicate melt but only as the result of some secondary process [*Wahl*, 1952] such as the accumulation of fragments resulting from the disruption of the primary body [*Lovering*, 1957]. Excluding these, it appears that only the non-polymict brecciated stony meteorites (that is, most of the achondrites) can be legitimately considered as primary samples of the differentiated silicate mantle of the parent meteorite body. In this way a new model can be drawn up for the mantle of the meteorite body. This new model will be discussed more fully in another place but the main features can be summarized as:

(1) A basal zone, situated just above the metal core, composed of dunitic material. The observed abundances of meteorites which formed in this basal zone would indicate that this zone comprised about five per cent by volume of the silicate mantle.

(2) An intermediate zone (about 35 pct) situated above the basal zone in which peridotitic and pyroxenitic achondrites formed.

(3) An outer zone (about 60 pct) in which basaltic or eucritic achondrites, with compositions very similar to terrestrial basalts and norites, have formed.

In Table 1 the mean composition of these eucritic achondrites is compared with the mean compositions of terrestrial norites (which form the parent

TABLE 1 - *Mean compositions of eclogites, olivine basalts, norites, and eucritic achondrites*

Compound	Mean eclogite 1	Mean olivine basalt 2	Mean norite 3	Mean eucritic achondrite 4
SiO_2	49.2	48.93	49.83	49.87
Al_2O_3	14.6	15.69	18.08	12.00
FeO^a	12.6	11.96	9.37	16.73
MgO	8.9	8.24	9.00	10.12
CaO	11.5	11.31	11.82	10.65
Na_2O	2.5	2.80	1.75	0.55
K_2O	0.7	1.07	0.15	0.08
Total[b]	100.0	100.00	100.00	100.00

[a] Fe_2O_3 converted to FeO.

[b] All analyses recalculated to 100.00.

1. Mean of 34 ecolgite analyses [*Lapadu-Hargues*, 1953].

2. Mean of 116 olivine basalt analyses [*Green* and *Poldervaart*, 1955].

3. Mean of published analyses of the noritic parent magmas from the Bushveld, Duluth, Sudbury, Belhelvie, Skaergaard, and New Zealand (North Island) differentiated intrusions.

4. Mean of 25 eucritic or basaltic achondrite analyses collected by *Urey* and *Craig* [1953].

magmas of certain differentiated and layered intrusions found near the Earth's surface) and olivine basalts, both of which may well represent the material at the base of the crust. From these data it is at once obvious that if the greater part of the Earth's upper mantle was composed of material similar in composition to the eucritic achondrites (as was the upper mantle of the parent meteorite body) then such material would have a composition which is essentially identical with rocks such as basalts or norites which probably form major components of the lower regions of the Earth's crust. It is true that the analyses of basaltic achondrites collected by *Urey* and *Craig* [1953] show a certain variability in composition but this would be expected if the basaltic achondrites formed a layered complex, as *Hess* and *Henderson* [1949] have concluded from their studies on the Moore County eucrite.

There is, then, no evidence from the new meteorite analogy to indicate that the Mohorovicic discontinuity is due to a major change in chemical composition which would be required if ultrabasic rock formed the Earth's upper mantle.

If the possibility of a chemical change is removed, then the only other explanation capable of accounting for the known physical properties of the upper-mantle rocks is that the Mohorovicic discontinuity represents a relatively narrow zone in which rocks of basaltic composition (including pyroxene granulites, somewhat higher-grade metamorphic equivalents of basalt) of mean density at zero pressure about 2.97 gm cm^{-3} are transforming into a high-pressure modification of basalt which, on *Bullen's* [1953] Earth model, has a density under the pressures operating in that region equal to that of olivine (that is, 3.32 gm cm^{-3}). It is suggested that the nature of this high-pressure modification of basalt is best represented by the dense rock-type eclogite (zero pressure density 3.35–3.6 gm cm^{-3}; mean about 3.4) on both petrological [*Turner* and *Verhoogen*, 1951] and geochemical grounds (see analyses of the average basalt and eclogite in Table 1).

The idea that eclogites might exist as a primary constituent of the Earth's mantle is by no means new, having been suggested previously by *Fermor* [1914] and again by *Holmes* [1927]. *Goldschmidt* [1922] proposed an Earth model in which eclogite formed a zone in the upper mantle between the levels 120 and 1000 km while *Birch* [1952], on evidence based on studies of the incompressibility, density, and other parameters of the mantle, suggested that depths to approximately 300 or 400 km in the mantle may be composed by eclogitic material. Recent experimental determinations of the pressure-temperature curve of the albite + nepheline → 2 jadeite transformation by *Robertson* and others [1957] would indicate that such a transformation which they have broadly compared with the basalt → eclogite transformation may well be taking place under the continents at the depths calculated for the Mohorovicic discontinuity.

The nature of the phase transformation—By means of the following simplified equations, *Turner* and *Verhoogen* [1951] have shown that olivine basalts and eclogites are chemically equivalent

$$\underset{\text{labradorite}}{[3\ Ca\ Al_2Si_2O_8 \ + \ 2\ Na\ Al\ Si_3\ O_8]} \ +$$

$$\underset{\text{olivine}}{3\ Mg_2Si\ O_4} \ +$$

$$\underset{\text{diopside}}{n\ Ca\ Mg\ (SiO_3)_2} \ \rightarrow \ \underset{\text{garnet}}{3\ Ca\ Mg_2Al_2\ (SiO_4)_3} \ +$$

$$\underset{\text{omphacite}}{[2\ Na\ Al\ (Si\ O_3)_2 \ + \ n\ Ca\ Mg\ (Si\ O_3)_2]} \ +$$

$$\underset{\text{quartz}}{2\ Si\ O_2}$$

By replacing labradorite by bytownite and olivine + diopside by pigeonite, a similar equation may be written to show how the eucritic achondrites (for example, the Moore County eucrite, see

Hess and *Henderson* [1949]) are also chemically equivalent to eclogites

$$\underset{\text{bytownite}}{[4\ \mathrm{Ca\ Al_2Si_2O_8} \ + \ \mathrm{Na\ Al\ Si_3\ O_8}]} \ +$$

$$\underset{\text{pigeonite}}{[8\ \mathrm{Mg\ Si\ O_3} \ + \ n\ \mathrm{Ca\ Mg(SiO_3)_2}]} \ \rightarrow$$

$$\underset{\text{garnet}}{4\ \mathrm{Ca\ Mg_2Al_2(Si\ O_4)_3}} \ +$$

$$\underset{\text{omphacite}}{[\mathrm{NaAl\ (SiO_3)_2} \ + \ n\ \mathrm{Ca\ Mg(Si\ O_3)_2}]} \ +$$

$$\underset{\text{quartz}}{5\ \mathrm{Si\ O_2}}$$

From these simplified equations it does not seem unreasonable to suggest that the course of the basalt → eclogite transformation involves the nucleation of new pyroxene (that is, omphacite) and garnet phases as a result of solid-state diffusion. If this is the case, then the speed of the reaction is very dependent on the diffusion constant of the ions involved in the transforming system and thus to a large extent upon the temperature at which the transformation is taking place. However there is ample evidence from their petrology to indicate that eclogites are extremely unstable rocks in the Earth's crust and that reactions which bring about their transformation to less-dense rock types can proceed in geologically short times even at the relatively low temperatures which generally exist in the outermost zones of the crust. Under anhydrous conditions eclogites on the Earth's surface often show evidence of at least partial transformation to basaltic-type rocks with omphacite being replaced by a myrmekite-like intergrowth of diopside and plagioclase. In the hydrous environment which is more common in near surface regions of the crust complete gradation may be traced from unaltered eclogite, through eclogite amphibolites containing relict garnet and omphacite together with newly generated plagioclase and hornblende, to amphibolites of normal composition [*Turner* and *Verhoogen*, 1951]. The time involved in these retrogressive metamorphic reactions may be geologically short. For example eclogites in the Franciscan of California appear to show every stage of retrogressive metamorphism to glaucophane schists, indicating a maximum time for their alteration of the order of 10^8 years.

Estimated pressure-temperature curve for the basalt → eclogite transformation—If the Mohorovicic discontinuity marks the position of the basalt → eclogite transformation in the Earth's mantle, then a knowledge of the various depths to the Mohorovicic discontinuity and the corresponding temperatures at these depths would enable an estimate to be made of the pressure-temperature curve for the transformation. For example the depth to the Mohorovicic discontinuity under the oceans is considerably less than the depth under the continents so that if the temperatures at each of these depths is calculated, then two points on the pressure-temperature curve are given. The temperature distribution in the crust is by no means well known and a recent summary by *Birch* [1955] has indicated how four widely varying distributions can arise depending on the particular set of more-or-less plausible assumptions which is used in the calculations.

For the present purpose typical values of the temperature at the Mohorovicic discontinuity under the oceans and under the continents are required and these are derived *ab initio* from the surface heat flux and an assumed typical distribution of radioactivity. The temperatures calculated are of the same order as those of *Birch's* [1955] curve B in the crust, but in the upper part of the mantle very different values would be obtained on the present assumptions.

In principle, the pressure and temperature at any depth below a point on the Earth's surface can be calculated from a knowledge of the heat flux at the point and the properties of the material below it. The heat flux may be regarded as a fundamental geophysical quantity which will ultimately be mapped at all points of the Earth's surface: at the present time the average value under the oceans is not significantly different from the average value of 1.2×10^{-6} cal cm^{-2} sec^{-1} on the land [*Bullard* and others, 1956] and, for simplicity and ease of comparison, this value will be used in both cases.

On the present hypothesis, the crust below the oceans is assumed to consist of typical olivine basalt with known thermal conductivity K_0, density ρ_0, and rate of radioactive heat generation per unit mass A_0, all constant, so that the temperature may be estimated fairly definitely. If the heat flux at the ocean bottom is H and the temperature there is 0°C, the temperature θ at depth x below the ocean floor is given by

$$\theta = (Hx - \tfrac{1}{2}\rho_0 A_0 x^2)/K_0 \cdots \qquad (1)$$

Using the typical values $H = 1.2 \times 10^{-6}$ cal cm^{-2} sec^{-1} [*Bullard* and others, 1956], $A_0 = 3.5 \times 10^{-14}$ cal gm^{-1} sec^{-1} [*Jacobs*, 1956], $K_0 = 0.0057$ cal cm^{-2} sec^{-1} (°C cm^{-1}) (the mean of all values in

Birch and others [1942]), $\rho_0 = 2.97$, values of the temperature at any depth can be found. A composite 'mean thickness' of the oceanic and continental crusts has been calculated from the most recent data of *Poldervaart* [1955] and *Ewing* and *Press* [1956]. Taking the average depth of the Mohorovicic discontinuity below the ocean floor to be 6 km, the temperature at this depth calculated from (1) is about 123°C, while the pressure at this depth for the case of an ocean of depth 5 km with 6 km of basalt of density 2.97 below it is about 2200 bars. This gives the point 0 on the curve I of Figure 1 which shows the temperature at any depth (expressed in terms of pressure) under the oceans as calculated from (1).

Temperatures under the continents are much more difficult to estimate because of the uncertainty in the depth of, and heat production in, the sialic layer. Taking as a model of the continental crust a layer of sialic material of depth x_1, thermal conductivity K_1, density ρ_1, and heat production per unit mass A_1 lying on a substratum of basalt of conductivity K_0, density ρ_0 and heat production A_0, the temperature θ at depth x is given by

$$\left.\begin{aligned} \theta &= (H - \tfrac{1}{2} A_1 \rho_1 x)\, x/K_1\,, \quad 0 < x < x_1 \\ \theta &= \frac{(2H - \rho_1 A_1 x_1)x_1}{2K_1} \\ &\qquad + \frac{(H - \rho_1 A_1 x_1)(x - x_1)}{K_0} \\ &\qquad\qquad - \frac{\rho_0 A_0 (x - x_1)^2}{2K_0}, \quad x > x_1 \end{aligned}\right\} \qquad (2)$$

where the temperature at the surface ($x = 0$) is taken to be 0°C and the heat flux to be H. Assuming the sialic layer to consist of 10 km [*Gutenberg*, 1951] of granodioritic material [after *Poldervaart*, 1955] with the typical values $\rho_1 = 2.76$, $A_1 = 1.2 \times 10^{-13}$ cal gm^{-1} sec^{-1} [*Jacobs*, 1956], $K_1 = 0.0065$ (mean of values in *Birch* and others [1942]) and with the values for basalt as used previously, the temperature at a depth of 35 km (a reasonable value for the depth of the Mohorovicic discontinuity under the continents), is found to be 480°C, the pressure there being 10,000 bars. This gives the point C on the curve II of Figure 1 which shows the temperature at any depth, (that is, pressure) under the continents as calculated from (2).

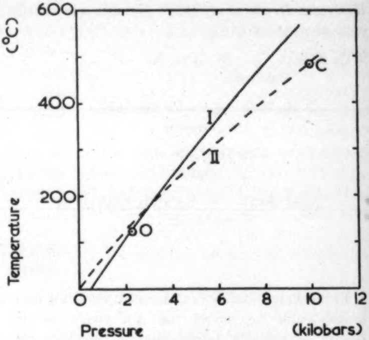

FIG. 1 – Distribution of temperature and pressure under the average ocean (I) and continent (II)

It appears from the relationship of curves I and II of Figure 1 that the variation of temperature with depth (or pressure) is determined more by the assumed value of the surface heat flux than by any other quantity. Small variations in the parameters will affect the relative positions of the curves (and in particular whether they cross as in Figure 1 and the place at which this occurs) but they will not alter the positions of the points 0 and C in order of magnitude and it may be assumed that $p - \theta$ curve for the reaction basalt → eclogite lies in the neighbourhood of the line 0C. This gives in order of magnitude

$$\frac{d\theta}{dp} = 0.046 \text{ where } \theta = 300°\text{C}$$

and since the change in volume is -0.046 cm^3 gm^{-1}, the Clausius-Clapeyron relation gives ΔH $= -14$ cal gm^{-1} which is of reasonable order of magnitude. Since $d\theta/dp$ is generally a function of θ or of p, the phase boundaries show some curvature but for the purposes of this study $d\theta/dp$ will be taken to be a straight line 0C given by the relation $p = 21.8\theta - 488$ where p is the pressure in bars and θ is the temperature in degrees centigrade (see Fig. 2).

It should be remarked that the above calculation has used values typical of oceanic and continental conditions in an attempt to establish approximately the position of the $p - \theta$ curve. If this latter is regarded as being known accurately, the depth of the Mohorovicic discontinuity at any point would be determined by the heat flux and the nature of the crustal material at the point in question; in particular under the oceans it would be determined almost entirely by the heat flux.

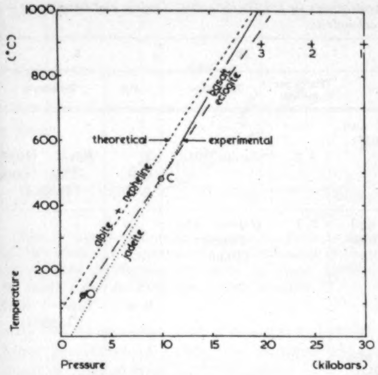

FIG. 2 – Estimated pressure-temperature curve for the transformation basalt → eclogite compared with theoretical [after *Kelley* and others, 1953] and experimental [after *Robertson* and others, 1957] equilibrium curves for the reaction albite + nepheline → 2 jadeite

This argument is independent of the source of the heat coming from below, that is, where it is provided by conduction or convection, provided that steady conditions prevail.

The temperature of 123°C derived above for the temperature at the Mohorovicic discontinuity under the oceans is suprisingly low and at first sight would seem to be too low for the basalt → ecologite reaction to proceed at a reasonable speed. However it has been pointed out earlier that eclogites show considerable evidence of being reactive at the relatively low temperatures which operate near the Earth's surface in times which are geologically small. It is, then, not unreasonable to expect the basalt → eclogite transformation to be proceeding at the oceanic Mohorovicic discontinuity level in geologically reasonable times.

Robertson and others [1957] have recently determined experimentally the equilibrium line for the reaction albite + nepheline → 2 jadeite, while *Kelley* and others [1953] had previously determined a theoretical line for the reaction from thermochemical data (see Fig. 2). The pyroxene 'omphacite' in eclogites is not pure jadeite ($NaAlSi_2O_6$) but may be regarded as a diopside-jadeite solid solution with some additional Al replacing Ca. *Robertson* and others [1957] have concluded that the pressure needed to form an omphacite pyroxene is probably less than that needed to form jadeite but in general it is to be expected that the equilibrium line for the formation of jadeite from albite and nepheline should be fairly close to that estimated for the formation of ecologite from basalt. From Figure 2 it is evident that this may well be the case.

The points given by *Coes* [1955] as representing the 'best conditions' for the formation of pyrope, pyrope + 5pct almandite, and grossularite are indicated in Figure 2 by the crosses 1, 2, and 3 respectively. The pyrope, and to some extent the pyrope + 5pct almandite points lie well within the eclogite field but grossularite is very close to the basalt → eclogite boundary. Now the garnet of eclogites is not a pure pyrope but is actually a lime-bearing almandite-pyrope with 25–70 pct pyrope and 12–40 pct grossularite [*Turner* and *Verhoogen*, 1951]. From Coes' data the equilibrium pressure of eclogite garnet at 900°C might be expected to lie between points 2 and 3 in Figure 2 and, as a result, lie less than five kilobars above the equilibrium pressure at 900°C for the basalt → eclogite reaction. On the basis of their experimental data *Robertson* and others [1957] found that Coes' 'best condition' point for jadeite at 900°C was about two kilobars above the equilibrium pressure at that temperature.

It should be pointed out that the use of a single line in the $p - \theta$ diagram to separate the stability fields of basaltic (that is, pyroxene and plagioclase) and eclogitic (that is, omphacite pyroxene and garnet) rocks is a simplification of the true situation since it is not yet established how many components are concerned even though it does seem likely that there are only two main phases involved on each side.

Geophysical implications—The suggestion that the materials above and below the Mohorovicic discontinuity have essentially the same composition, being separated by a phase change, has consequences of great geophysical importance. Firstly, it implies that the concentration of radioactive elements, and hence the heat production per unit mass, should be the same throughout the extent of the material in both phases, a point which was made previously for the calculation of temperature-depth curves in the oceanic and continental crust.

This immediately removes the well-known difficulty involved in finding a source for the heat flux from the oceans which is known to be of the same order of magnitude as that from the continents. If the material below the Mohorovicic discontinuity is assumed to be ultrabasic in charac-

TABLE 2 – *Uranium, thorium and potassium concentrations in basalts, eclogites, dunites and basaltic (eucritic) achondrites*

Sample	Name or locality	U		Th		K	
		Parts per million	Reference	Parts per million	Reference	Pct	Reference
Basalts	Hualalai	0.46	*Hamaguchi* and others [1957]	...	...	...	...
	Average	0.6	*Birch* [1955]	3.2	*Jacobs* [1956]	1 0.9	*Birch* [1955] This work (Table 1)
Eclogites	South African diamond pipes	uncorrected mean 1.13 corrected 0.5[a]	*Holmes* and *Paneth* [1936]	1.3	*Holmes* and *Paneth* [1936]	...	...
	Average	...	...	...	...	0.6	This work (Table 1)
Dunites	Twin Sisters	0.001	*Hamaguchi* and others [1957]	...	...	...	...
	Average	0.015	*Birch* [1955]	0.046	*Jacobs* [1956]	0.001	*Birch* [1955]
Basaltic or eucritic achondrites	Nuevo Laredo	0.2	*Patterson* [1955]	0.7	*Patterson* [1955]	0.047	*Edwards* [1955]
	Pasamonte	0.126	*Hamaguchi* and others [1957]	...	...	0.055	*Edwards* [1955]
	Average	...	...	...	...	0.05[b]	*Edwards* [1955]

[a] From data given by *Smales* [1952].

[b] Average of ten.

ter with the low radiogenic heat production of known ultrabasic rocks it is extremely difficult to account for this equality and other explanations, such as convection in the mantle, have been invoked [*Bullard* and others, 1956]. On the other hand, if the material below the Mohorovicic discontinuity has a composition similar to that of a basaltic rock with a similar high rate of radiogenic heat production (of the order of 3.5×10^{-14} cal gm^{-1} sec^{-1}), it appears that the whole heat flux of 1.2×10^{-6} cal cm^{-2} sec^{-1} could be produced by a layer of such material about 100 km in thickness. If the concentration of radioactive elements diminishes even only slightly with depth, as seems geochemically likely, it would be possible that this material extended to a depth of 200–300 km implying that the region B of the mantle might well be composed of such material (that is, eclogite).

The few data available on the concentration of radioactive elements in eclogites and achondritic meteorites have been summarised in Table 2. *Holmes* and *Paneth* [1936] determined the uranium and thorium contents of a number of inclusions in the South African diamond pipes including three eclogites and three zircon crystals. *Smales* [1952], using a radioactivation technique, redetermined the uranium contents of the same three zircon crystals and found values considerably lower than they had reported. There is then good reason to suppose that the uranium contents of the three eclogites reported by *Holmes* and *Paneth* [1936] are also too high and in Table 2 their values have been corrected by Smales' factor (average 0.43 calculated from the zircon analyses) to bring them into line with his presumably more accurate analytical technique. It is then apparent that the uranium, thorium, and potassium contents of basalts and eclogites are sufficiently alike for eclogitic rocks to be a suitable material for the upper part of the Earth's mantle.

From the meteorite analogy it follows that the general level of concentration of radioactive elements in the basaltic or eucritic achondrites should be similar to that of their suggested terrestrial equivalents (that is, basalts and eclogites). The data in Table 2 indicate that the levels are similar although the absolute values are somewhat lower. Since many of these achondrites have presumably formed at greater relative depths in their parent body than those basalts and eclogites available for analysis have in the Earth, these achondrites

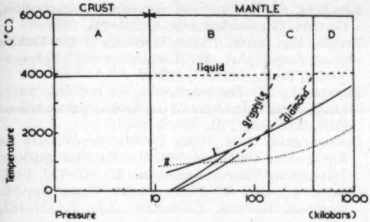

FIG. 3 – The graphite-diamond stability fields in the Earth's crust and upper mantle from estimates of the temperature distribution according to *Jacobs* [1956] for curve I and to *Verhoogen* [1956] for curve II

may well be expected to have retained a slightly lower proportion of radioactive elements as a result of more advanced differentiation.

The occurrence of certain accessory minerals in terrestrial eclogites may be used to estimate the depths in the Earth's mantle from which eclogitic rocks have apparently been derived. It is well known that certain eclogites contain diamonds so that the minimum depth in the mantle from which such eclogites could have come may be calculated by the minimum depth in the mantle at which diamond becomes stable. The equilibrium curve for the graphite → diamond transformation is fairly well established even up to temperatures of around 4000°C as a result of the experimental work of *Bundy* and others [1955] and is given in Figure 3. Also included in this figure are two estimates of the temperature distribution in the upper mantle recently proposed by *Verhoogen* [1956] and *Jacobs* [1956]. With increasing depth these estimates are widely variant but in the region of the upper mantle agreement is reasonably satisfactory. From Figure 3 it is apparent that diamond becomes stable in the mantle at depths of from 130–190 km so that eclogites containing diamond must have formed at least at these depths which are well within Region B. Other eclogites (that is, those containing quartz as a primary constituent) must have formed at considerably shallower depths since from what is known about the quartz → coesite transformation, quartz cannot exist at depths greater than 60–100 km [*MacDonald*, 1956].

A second consequence, and one with important geochemical and petrological implications, is that the 'primary magma' from which the various chemical rock types in the mantle have differentiated must have a composition closer to basic rather than to ultrabasic silicate material (as had been thought to be the case previously). It has long been a problem to derive the granitic and basaltic components of the Earth's crust by the differentiation of the ultrabasic material which was thought to make up the material in the Earth's mantle [*Voytkevich*, 1955]. If a good deal of the upper mantle is composed of rock of basaltic composition, as follows from this work, then this problem no longer exists.

A third consequence, and probably the most important one, is the mechanism which this concept for the nature of the Mohorovicic discontinuity provides for certain regions of the Earth's crust to be raised relative to adjacent static regions simply by increasing the temperature at the Mohorovicic discontinuity under the mobile tract. Such a temperature rise at the base of the crust would follow the final stage of a convective overturn of the type envisaged by *Griggs* [1939] as operating in the mantle. The temperature at the discontinuity will rise and the position of the discontinuity will become unstable and should, as a consequence of Figure 2, sink to greater depths. The eclogitic material which originally existed between the original and final levels of the discontinuity will transform to basaltic material with a volume increase of something like 15 pct. It is the volume increase which then provides the mechanisms for raising the overlying crustal column relative to adjacent regions under which the Mohorovicic discontinuity has been unaffected. Similarly a decrease in temperature at the base of the crust would cause a depression at the Earth's surface above this region. It is immediately obvious that this process has far-reaching geophysical implications. For instance the existence of the so-called 'roots' under uplifted mountain ranges, as well as the uplifting mechanism itself, follows as a direct result of an assumed temperature rise at the base of the crust under these regions. A more detailed discussion of these and other geophysical implications will appear in another place.

Conclusions—By analogy with a new model for the mantle of the primary meteorite body, the depth to which silicate material of basaltic composition should exist in the Earth must be increased far beyond the currently accepted limit which is taken to be the Mohorovicic discontinuity. Consequently the Mohorovicic discontinuity itself may not mark a chemical change from basaltic material in the lower crust to ultrabasic material in the upper mantle but rather a zone in which basalt is transforming to a high-pressure modification, most likely represented by the dense rock-type eclogite. Since the levels of the Mohorovicic discontinuity under oceans and continents are different then calculations of the temperatures and pressures at each of these depths gives two points on the equilibrium curve for the basalt → eclogite transformation which appears to be a line roughly given by the relation $p = 21.8\theta - 488$. The 'equilibrium line' is in general agreement with the latest experimental data for the formation of the pyroxenes and garnets found in eclogites. The geophysical consequences of a phase change at the Mohorovicic discontinuity are far-reaching and include the predicted equivalence of oceanic and continental heat flows, a satisfactory 'parent magma' from which the granitic and basaltic crustal zones could have differentiated as well as providing a mechanism by which certain regions of the Earth's surface can be raised vertically simply by causing an increase in temperature at the base of the crust beneath that region which results in the Mohorovicic discontinuity being displaced downwards and a certain amount of high-density material transforming into a less-dense modification with a corresponding volume increase.

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A^{40}/K^{40} Age of Gneiss from McMurdo Sound, Antarctica

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Abstract—Biotite from paragneiss of Gneiss Point, McMurdo Sound, Antarctica is dated at 520 m y by the A^{40}/K^{40} method. Metamorphism of Precambrian sediments at the close of Precambrian or in Cambrian time is indicated, but additional work is needed.

Introduction—Paragneiss bedrock from Gneiss Point on the west side of McMurdo Sound, Antarctica (Fig. 1) is dated at 520 million years by A^{40}/K^{40} analysis of biotite separated from the gneiss. The sample was collected by R. P. Goldthwait and A. L. Washburn during a short reconnaissance to Gneiss Point in December, 1957, in the course of investigations sponsored by the U. S. National Committee, International Geophysical Year.

The dated specimen (57-12-3d) was collected from the crest of the most prominent hill on Gneiss Point (approximately, lat. 77°25′S, long. 163°43′ E). West of this locality there is a belt of coarsely crystalline white marble trending roughly north-south across the point, and other rock types occur west of the marble belt. According to *Smith* and *Debenham* [1921, p. 144] the metamorphic rocks along the coast in this vicinity "....comprise a considerable thickness of schists and crystalline limestones, probably associated with pyroxene-granulites; and represent metamorphosed argillaceous, calcareous, and dolomitic sediments. In addition to this sedimentary series there is an intrusion, probably quite considerable, of biotite-hornblende gneiss and some amphibolites and hornblende-schists probably representing altered dyke-rocks."

Description of sample—Specimen 57-12-3d is a dark-gray, medium-grained gneiss with well-developed compositional banding. Biotite is abundant in the mafic layers. The light-colored feldspar-quartz bands are considerably coarser in grain than the dark bands. The gneiss undoubtedly is of sedimentary origin, and the sample cannot be considered to be representative of the bedrock of the vicinity; however, a point-count analysis of a thin section gives the following mode: andesine (An_{35}), 38 pct; biotite, 30; hornblende, 20; augite, 6; and quartz, 6.

Orthoclase (one per cent or less) is included with the andesine, because it is largely in antiperthite. Accessory minerals, probably less than one per cent, include apatite, sphene, and zircon. Pleochroic halos around these minerals are well developed in the biotite. Some of the hornblende developed at expense of augite as is indicated by irregular relicts of pyroxene, and there is some sericite in the andesine. There is a trace of chlorite formed from the biotite, but the rock is remarkably fresh and unaltered. The sample is classified as biotite-hornblende-andesine paragneiss and indicates metamorphism of rather high-grade amphibolite facies.

Biotite was separated from crushed material (40–60 mesh) with a Franz Isodynamic separator and was estimated to be 95 pct or more of the final separate, the principal impurity being hornblende. Determinations in the Rock Analysis Laboratory gave 8.33 and 0.06 pct for K_2O and Rb_2O, respectively. Two determinations of A^{40} gave 1.57×10^{-4} and 1.58×10^{-4} cc STP/gm, and the A^{40}/K^{40} ratio is 0.0333. The empirical values of 0.557×10^{-10}/yr for λ_e and 4.72×10^{-10}/yr for λ_β [Wetherill and others, 1956] give an age of 520 m y.

Discussion—The stratigraphy and structure of Antarctica have been summarized recently by *Davies* [1956], and the petrology by *Stewart* [1956]. Gneiss Point is part of the East Antarctica Precambrian shield composed of metamorphic and intrusive crystalline rocks that are overlain by sedimentary series of lower Paleozoic and of Mesozoic age. The East Antarctica shield is set off from the folded Mesozoic and Cenozoic rocks of West Antarctica by a large fault or fault zone. The upthrown segment of this fault which extends from McMurdo Sound to the Weddell Sea, skirting the South Pole, has been called the Great Antarctica Horst and constitutes one of the major tectonic features of Antarctica [*David* and *Priestley*, 1914; *Fairbridge*, 1952].

Gneiss Point is situated on the great fault zone and also is in close proximity to the volcanic islands of the Ross Sea of which Ross Island is active. For these reasons geologic interpretation of the 520 m y age must be cautious. Specifically, the date supports the Precambrian age assigned by

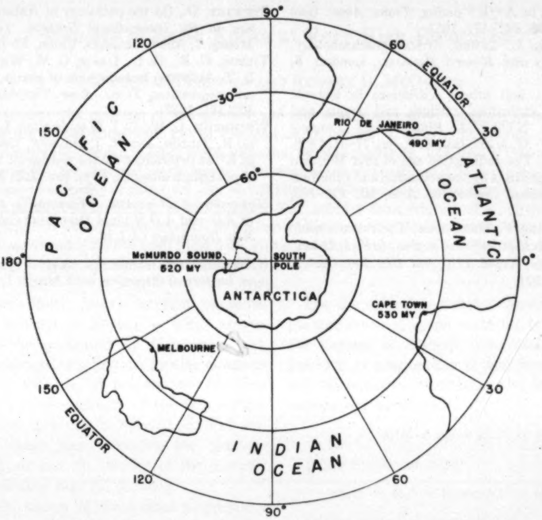

FIG. 1 – Sketch map showing location of dated sample from McMurdo Sound, Antarctica

geologists to the East Antarctica shield. If it is assumed that the rocks of Gneiss Point have not been affected by events subsequent to the formation of the paragneiss, it can be said that the metamorphic rocks mark an orogeny essentially at the close of Precambrian or in Cambrian time. Some support for this hypothesis is afforded by by A^{40}/K^{40} dates of 490 m y [*Goldich*, *Baadsgaard*, and *Nier*, 1957] for biotite from gneiss at Rio de Janeiro, Brazil and of 530 m y for the Cape Town granite [*Tilton* and others, 1957]. These dates, as well as others [*Holmes* and *Cahen*, 1955] suggest the possibility that there was a period of orogeny and intrusion at the close of Precambrian time. Further work on rocks from Antarctica may help to establish or to eliminate the hypothesis, and certainly a major contribution to the geology of Antarctica can be made by dating rocks from the scattered and poorly known outcrops of this vast continent. That some ancient rocks will be found in Antarctica seems assured by radioactive ages in the range 2.6–2.8 b y that have been reported from Minas Gerais, Brazil [*Hurley* and others 1958], Western Australia [*Jeffery*, 1956] and Southern Rhodesia [*Holmes* and *Cahen*, 1955].

To the writers' knowledge the data here reported for the gneiss of McMurdo Sound is the first radioactive age determination of a rock from Antarctica.

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Density of Basic Rocks at Very High Pressures

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Abstract—The densities of two gabbros and one dunite have been measured at several pressures in the range from 150 to 750 kilobars (1 kilobar = 986.9 atmospheres). These pressures were attained in shock fronts generated by high explosives. The densities were computed from the observed shock waves. The dunite, initial density of 3.25 g/cc, was compressed to a density of about 4.9 g/cc at 720 kilobars. The gabbros, initial density 3.0 g/cc, were compressed to 5.0 g/cc at 750 kilobars. Both gabbros show evidence of a polymorphic transition at some pressure around 150 kilobars to a more dense, but less compressible phase. The agreement obtained from these data with a crust of dunite 400 kilometers thick underlain by a gabbroic rock with Bullen's Model A is very close.

Introduction—Shock fronts carrying pressures up to 1000 kilobars (1 kilobar = 986.9 atmospheres) may be generated by high explosives. High-speed photography permits precise measurements of the velocity of propagation of these shock fronts and the velocity of the free surface when the shock pressure is relieved at that surface. From these two velocities the pressure behind the front and the density of the material under this pressure may be deduced.

Theory—The theory of shock front propagation is very simple compared to the theory of large amplitude wave motion. The basic equations will be reviewed briefly following the notation and development of *Courant* and *Friedrichs* [1948, pp 107–160]. Any material in which the sound speed increases as the material is compressed will transmit compressive shock fronts. Qualitatively this is easy to understand since if two compressive wave fronts are traveling in the same direction the second wave is moving through material already compressed by the first. It is therefore traveling faster and will overtake the first. Any large amplitude disturbance will then become a shock if dissipation processes, such as viscosity or heat conduction, do not remove too much energy.

Figure 1 illustrates the propagation of a shock front through one material and into a second material the other face of which is free, that is, bounded by gas at atmospheric pressure. In all materials and states ρ is the density, τ is the specific volume, u is the particle or material velocity, P is the pressure, and U is the shock front velocity. Even subscripts denote value of parameters before the arrival of the initial shock front, odd subscripts values after the first shock front, and primes the values after the second front.

Let the subscripts i and f denote values of the parameters in a given material before and after the passage of a shock front and let U be the velocity of propagation of the front. The fundamental equation connecting the initial and final values may be written

$$\rho_i(U - u_i) = \rho_f(U - u_f) \tag{1}$$

(conservation of mass)

$$\rho_i(U - u_i)^2 + P_i = \rho_f(U - u_f)^2 + P_f \tag{2}$$

(conservation of momentum)

$$\begin{aligned}\rho_i(u_i - U)(\tfrac{1}{2}u_i^2 + e_i) + P_iu_i \\ = \rho_f(u_f - U)(\tfrac{1}{2}u_f^2 + e_f) + P_fu_f\end{aligned} \tag{3}$$

(conservation of energy)

where e is the specific internal energy or energy per unit mass. Considering only the first two equations these contain seven parameters. The initial parameters ρ_i, u_i, P_i may be considered known; thus if any two of ρ_f, u_f; P_f, or U can be measured, the remaining ones can be computed. Practically, u_f and U are measured and ρ_f and P_f computed.

Introducing the specific volume $\tau = 1/\rho$ and taking u_i and P_i to be zero, Eqns. (1) and (2) reduce to

$$\tau_f = \tau_i(U - u_f)/U \tag{4}$$

$$P_f = \rho_iUu_f \tag{5}$$

Thus if U the shock velocity and u_f the particle velocity can be measured, the pressure and specific volume or density behind the shock front can be calculated. Several methods of making these measurements have been described [*Walsh*, 1955; *Minshall*, 1955; *Bancroft*, 1956].

The temperatures may be calculated by using certain thermodynamic identities [see, for ex-

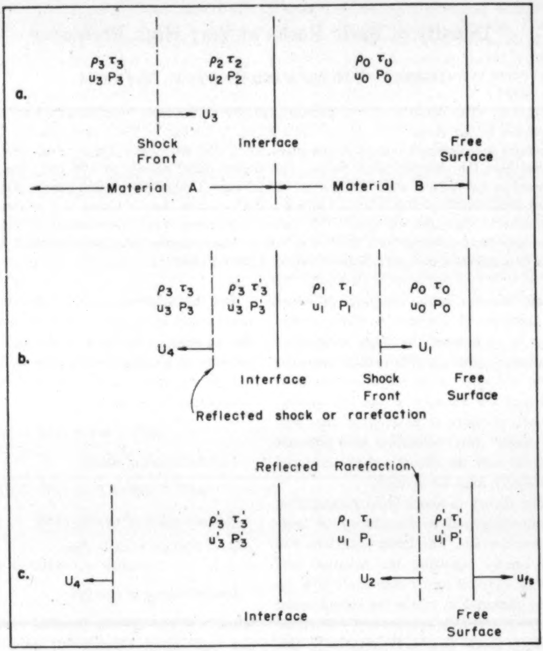
a.
ρ_3 τ_3
u_3 P_3
ρ_2 τ_2
u_2 P_2
ρ_0 τ_0
u_0 P_0
U_3
Shock Front
Interface
Free Surface
Material A
Material B
b.
ρ_3 τ_3
u_3 P_3
ρ_3' τ_3'
u_3' P_3'
ρ_1 τ_1
u_1 P_1
ρ_0 τ_0
u_0 P_0
U_4
U_1
Interface
Shock Front
Free Surface
Reflected shock or rarefaction
c.
Reflected Rarefaction
ρ_3' τ_3'
u_3' P_3'
ρ_1 τ_1
u_1 P_1
ρ_1' τ_1'
u_1' P_1'
U_4
U_2
u_{fs}
Interface
Free Surface

FIG. 1 – Shock wave propagation across interface

ample, *Walsh*, 1955]. The final equation is

$$T_1 = T_0 \exp[b(\tau_0 - \tau_1)] + \exp(-b\tau_1)\int_{\tau_0}^{\tau_1} [f(\tau)\exp(b\tau)/C_\tau]_{\mathrm{Hug}}\, d\tau \quad (6)$$

where τ_0 is the initial specific volume
τ_1 is the final specific volume
T_0 is the initial absolute temperature
T_1 is the final absolute temperature
$b = (\partial P/\partial T)_\tau/C_\tau$
C_τ is the specific heat at constant volume
$f(\tau) = [(\tau_0 - \tau_1)(dP/d\tau) + P]/2$

The first term on the right of (6) is the temperature rise associated with an isentropic process; the second term is a correction that takes account of the fact that the shock process is nonisentropic.

The integral is taken over the Hugoniot curve in the $P - V$ plane. This curve is the locus of $P - V$ states that can be reached from some initial P_0V_0 state by shock processes. It differs very little from the adiabatic [*Courant* and *Friedrichs*, 1948, p. 138].

To obtain the pressure and density behind the shock, U and u_f must be determined. The shock velocity U can be measured directly but u_f cannot be measured directly. Referring to Figure 1*c*, u_{fs}, the free-surface velocity of the material, can be measured [*Walsh*, 1955; *Minshall*, 1955]. With very weak shocks (sonic waves) u_{fs} would be exactly $2u_i$. This is not true for shocks of the strength considered here; however it can be shown that [*Walsh*, 1955]

$$1 - \delta < u_{fs}/2u_f < 1 + \delta \quad (7)$$

where for most solids δ is of the order of 0.03; in particular this is true of the rocks considered here. Actually this error could be eliminated at

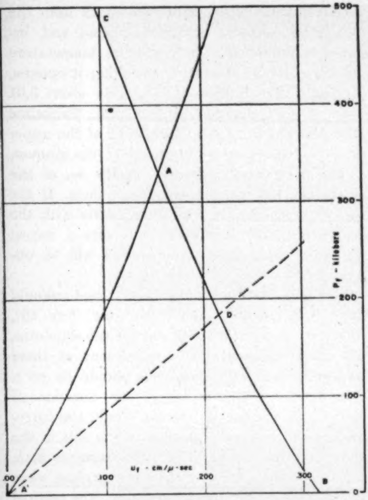

FIG. 2 – Hugoniot and adiabat for aluminum

the cost of rather elaborate computations, but it is unimportant in the present work.

Curve *A'A* in Figure 2 shows the experimentally determined relation between P_f and u_f in 24*S-T* aluminum. This curve can be derived by using (4) and (5), and the published data [*Walsh*, 1955, Table 2]. Consider point *A* in Figure 2; this represents a shock of about 330 kilobars into aluminum, the particle velocity is 0.16 cm/μsec, the shock velocity is about 0.76 cm/μsec. When this shock reaches a free surface the material at the surface which is under this pressure starts expanding. In doing so it follows the curve *AB*. If *CAB* is drawn as the mirror image of *AA'* with respect to the vertical through *A*, the particle velocity at *B* will be exactly twice the particle velocity at *A*. Actually the curve segment *AB* represents adiabatic states whereas the segment *AC* represents left-going shocks propagated into the aluminum after being shocked to state *A* by a right-going shock. It is not exactly a mirror image of the corresponding segment of *OA*, neither is it a continuation of the adiabatic from *A* to *B*, but it differs very little from either of these.

Consider the situation in Figure 1b; the shock in material *A* has reached the interface, a shock is being propagated into material *B*, and a reflected shock or rarefaction is traveling to the left in material *A*. Assume that material *A* is aluminum and that u_3, P_3, and U_3 are known and that U_1 in Figure 1b is measured. Now from (5)

$$P_1 = \rho_0 u_1 U_1 \qquad (9)$$

where P_1 and u_1 are at present unknown. Since u_3 and P_3 are known the point *A* on the aluminum curve is determined. Following the shock the aluminum must move along either *AC*, reflected shock, or along *AB*, reflected rarefaction into the aluminum. In (9), ρ_0 and U_1 are known; draw the straight line *OD* in Figure 2 with slope $\rho_0 U_1$, then the point *D* (in Figure 2) represents conditions at the interface between the aluminum and material *B* in Figure 1. As drawn a rarefaction is reflected into the aluminum. If *D* had fallen above *A* on *AC* a shock would have been reflected into the aluminum. Point *D* is then one point on the curve of the relationship of *P* to *u* of material *B*. By creating shocks of different strengths in the aluminum as many points as desired can be determined on the curve for material *B*, and then from (4) and (5) curves of the relationship of pressure to volume or pressure to density for material *B* can be drawn.

Anisotropy of the medium seems to be unimportant in this work. Even as anisotropic a material as zinc, in which the longitudinal wave velocities parallel and perpendicular to the *c*-axis are about 0.279 cm/μsec and 0.474 cm/μsec, shows no detectible shock wave anisotropy [*Walsh*, *Rice*, and *McQueen*, 1957].

Experimental method—The experimental method is the same as that described by *Walsh* and others [1955, 1957]. A cone of high explosive is built up of shells of high- and low-speed explosives in such a combination that when detonated at the apex the detonation front is accurately plane and perpendicular to the axis when it reaches the base of the cone. The base diameter is about ten inches, a block of uniform explosive ten inches in diameter and two to four inches thick is placed on the base of the cone, an aluminum plate about 12 × 12 inches is placed on the block. After detonation a plane shock wave travels through the aluminum plate. The strength of this shock will depend upon the composition and thickness of the high-explosive block. Since the shock in the aluminum is attenuated with distance of travel, the strength of shock reaching the front surface of the plate can be changed by using plates of different thickness.

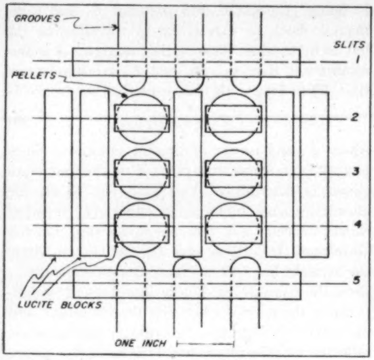

FIG. 3 – Layout of target plate

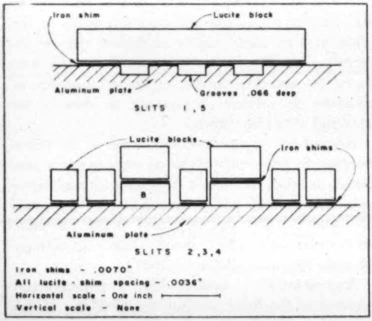

FIG. 4 – Cross section of target plate

Figure 3 shows one possible experimental layout on the front surface of the aluminum plate. Figure 4 shows cross sections at the relevant points. A thin aluminum plate with slits cut as shown in Figure 3 is placed over the assembly but is not shown in Figure 4.

In Figure 4 consider a shock wave being propagated upwards in the aluminum plate. The shock wave first hits the bottoms of the grooves which then move with a constant velocity u_{f_3} determined by the shock strength and the fact that the material is aluminum. The shock front itself hits the front of the aluminum plate and throws the iron shim upwards closing the gap between the iron shim and the lucite. This space is filled with argon gas which under the shock from the iron shim becomes brilliantly heated and intensely luminous. The intense temperature quickly destroys the lucite, rendering it opaque, so that a very brilliant flash of only about 0.01 μsec or less duration is produced. Sometime after the arrival of the shock front at the upper surface of the plate the bottoms of the grooves, which are moving with the velocity u_{f_3} of the aluminum, hit the iron shim over them. If the system is scanned by a rotating mirror with the axis of rotation parallel to the slits a record similar to that shown in Figure 5 will be obtained.

In Figure 5 all traces of *a*, *b*, *c*, *d*, and *e* should have been made at the same time. Any tilt, curvature, etc. of the shock wave in the aluminum will cause distortion or displacement of these traces, so that the segments *a* should lie on a straight line perpendicular to the direction of motion, the spacings *ab*, *bc*, etc. should also correspond to the physical spacings of the slits in the plate over the charge. Thus, the segments *a*, *b*, and *c* show the quality of the incident plane wave and provide a time zero for each slit. The vertical distance *aa′* multiplied by the known scanning rate of the camera gives the time between the shock wave hitting the shim and the bottom of the groove hitting the shim.

If d is the depth of the groove, U_3 the shock velocity in the aluminum and u_{f_3} the free-surface velocity of the aluminum, this time is obviously $t = d/u_{f_3} - d/U_3$. Now as discussed above, $u_{f_3} = 2u_3$, and this equation may be written

$$1/V_B = t/d = 1/2u_3 - 1/U_3 \qquad (10)$$

From (5), $P_3 = \rho_2 U_3 u_3$, where P_3 is the pressure in the aluminum behind the shock. With (10) and the data of Figure 2 a plot of V_B vs P_3 can be prepared. From the data of slits 1 and 5 several independent values of V_B and hence P_3 can be determined, and hence the pressure of the shock wave in the aluminum and its uniformity over the plate can be measured.

This experimental layout was developed primarily so that very small samples of material could be used. Referring to the lower section of Figure 4 the pellet B is a disc about 0.750 inch in diameter and about 0.250 inch thick. In Figure 5 the displacement *bb′* gives directly the time necessary for the shock wave to traverse this pellet, and hence U_1 of Figure 1b is measured directly. Then as discussed above under *Theory*, the line *OD* of Figure 2 may be drawn and P_1

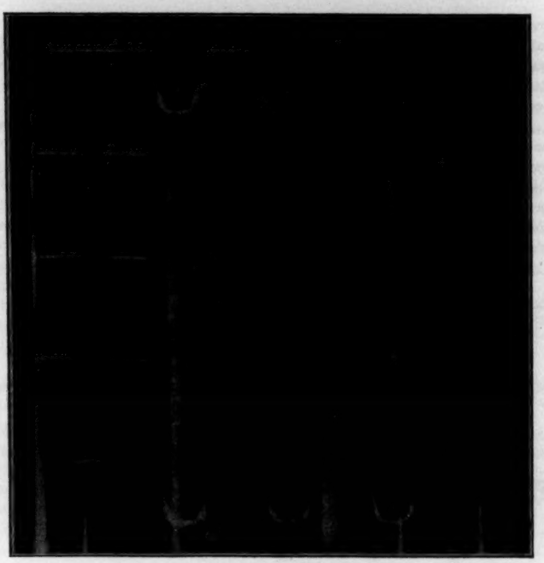

FIG. 5 – Reproduction of camera record

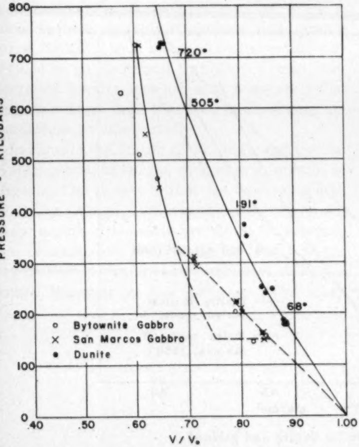

FIG. 6 – Pressure-volume curves of dunite and gabbros

and u_1 of Figure 1 determined. From (4) the compression or specific volume under this pressure is calculated. As shown in Figure 3 there is space for six pellets on each shot.

Figure 5 is a reproduction of the plate obtained on shot 915. The two lower pellets were dunite (from Jackson County, N. C.), the two on the upper right were San Marcos gabbro (from Escondido, Calif.) and the two on the upper left bytownite gabbro (from Duluth, Minn.). The pellet traces are displaced almost the slit distance in this shot. This is a particularly good record in that all pellets gave a good clear trace.

Discussion of results—The gabbros sometimes gave a very irregular, wavy trace. The irregularities correlate roughly with specimen quality; the bytownite gabbro contains crystals 5 to 10 mm in diameter, while for the San Marcos gabbro the crystals are only 1 to 2 mm in diameter. In Figure 6 it is seen that the spread of bytownite gabbro points is much greater than that of San Marcos gabbro points. Further, the bytownite gabbro points that fall off the curve in Figure 6 are all of low density, 2.80–2.85 instead of 3.0 g/cc. The data on the dunite also shows considerable spread, although this rock is homogeneous. Complete petrographic descriptions of these rocks have been published [*Hughes* and *Maurette*, 1957].

Despite the scatter of the dunite points, the Hugoniot curve obtained is typical of that found for most solids. The gabbros, however, have an unusual property; the wave velocity is constant up to 300 kilobars, after which the shock velocity versus particle velocity curve again assumes a typical slope (see Fig. 7; the zero-pressure wave velocity plotted in Fig. 7 is that obtained from *Hughes* and *Maurette* [1957]). Such a curve is evidence of a polymorphic transition [*Minshall*, 1955; *Bancroft*, 1956] where the disturbance, instead of consisting of a single shock wave, manifests itself as two shock waves propagating at different velocities. The first wave propagates into undisturbed material and the state behind it is a point on the transition phase line for which the transition is just beginning to occur. The second shock wave propagates into the latter state and, depending upon the strength of this shock wave, the state behind corresponds to either a complete or incomplete transition. If the pressure carried by the second disturbance is sufficiently high, the transition is complete and the two waves coalesce (or, rather, in the present experiments, never separate). The data for the present gabbro are compatible with a polymorphic transition in the vicinity of 150 kilobars and an associated two wave structure, for pressures behind the second wave which are less than 300 kilobars. Obviously, the impedance-match solutions and consequent pressure-compression data for the gabbros in the 150–300 kilobars depend upon the assumption of a single shock wave and are invalid.

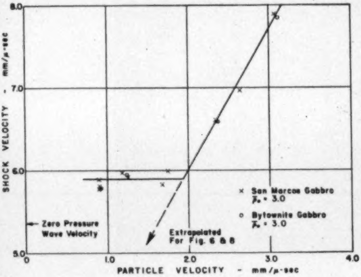

FIG. 7 – Shock propagation velocity vs particle velocity for gabbros

The above argument rests basically on the fact that the data of Figure 7 should be represented by two straight lines rather than a curve.

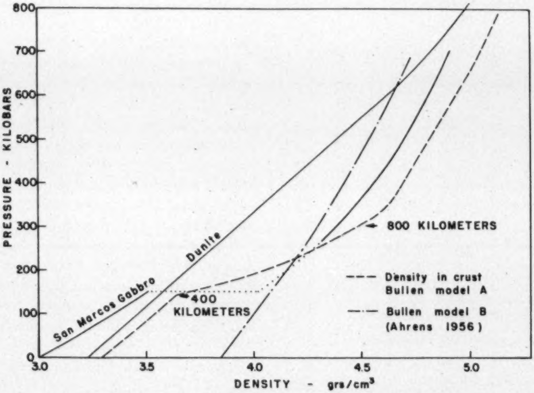

FIG. 8 – Density vs pressure for dunite and gabbros

We now have very good data on 27 metals, two ceramics, Plexiglas, and 17 alkali halides. For all these materials the plots of the relationship shock velocity to particle velocity are very accurately straight lines. Further, the slope of these lines is very closely correlated with the hardness of the material. The ceramics, plastics, and the alkali halides give slopes about the same as Figure 7 beyond 2.0 mm/μsec. The metals show about the same slope as the straight line that could be drawn through the points below 2.0 mm/μsec. Thus, however we interpret the data, it seems evident that the gabbros are quite different materials in the two ranges [*Duff* and *Minshall*, 1957].

If a material has a transition at, say, 100 kilobars, and is subjected to a greater pressure, a wave carrying 100 kilobars will run followed by a wave in the 'new' material carrying the remainder of the pressure. With single-shot methods such as we used here we can only observe the first wave. Hence, for all pressures above 100 kilobars we would only observe a 100 kilobar wave until the pressure rose high enough that the velocity in the 'new' material is faster than the 100 kilobar wave.

The relationship of P to ρ for the gabbros, Figure 8, has been computed on the assumption that these rocks undergo a polymorphic transition in the neighborhood of 150 kilobars. The transition is indicated by a constant pressure line which is joined to the downward-extrapolated high-pressure curve. Actually, such a zero slope line would correspond to an isothermal transition. Energy consideration for the dynamic case, however, would indicate a finite slope which the present data are not sufficient to determine.

In Figure 8 the density of the dunite and the San Marcos gabbro have been plotted as a function of pressure. The density within the crust computed by Bullen [*Ahrens*, 1956] on the basis of two different models of the earth are shown for comparison. It is apparent that the Bullen Model A density-pressure curve is closely represented by the dunite Hugoniot at low pressures. The sharp break in the Bullen Model A curve at 400 kilometers (about 150 kilobars) is also compatible with an assumed gabbro structure at that depth and the associated polymorphic transition. Finally, there is again good agreement between the gabbro Hugoniot and this model at pressures above 300 kilobars.

It is planned to extend the present shock-wave work by using pure minerals corresponding to the important constituents of these rocks. Such materials should, in particular, permit precise Hugoniot measurements and a more complete experimental study of any transitions.

Acknowledgment—This work was done under the auspices of the Atomic Energy Commission.

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Discussion of "Sky Temperatures in the Imperial Valley of California"

BY C. F. KELLY, T. E. BOND, AND N. R. ITTNER

[*Trans.*, **38**, 308–313, 1957]

Alice M. Stoll (Aviation Medical Acceleration Laboratory, U. S. Naval Air Development Center, Johnsville, Pa.; received Oct. 10, 1957)—It is gratifying to see that progress is being made along the lines of evaluating the cooling power of the sky with respect to physiological thermal exchange.

This paper recalled to mind a body of data collected by *Sissenwine* (then Head of the Environmental Physics Unit, Research and Development Branch, Military Planning Division, Office of the Quartermaster General) and others [1951] in July and August of 1950 in Death Valley. The proximity (about 250 mi) and obvious similarities in climate of this locality and Imperial Valley are such that there should be, and in fact are, similarities in the observed data, some of which, for ready reference and by way of example, are shown summarized in Table 1. The instruments used are described by *Sissenwine* and others [1951], *Richards* and others [1951], and *Stoll* and others [1952]. The table headings are largely self-explanatory. The sky temperatures shown are for an angle of about 1.1 steradians

TABLE 1 – *Daytime radiation loads in Death Valley, 1950*[a]

Date	Pac Std Time[d]	Eppley pyrheliometer[b]		Panradiometer							Thermal radiometer[b]		
		Solar radiation on horizontal plane		Normal direct solar radiation	Solar radiation on sphere 1m² in area			Radiant temp. of surroundings	Air temp.	Radiant loads on naked man[c]	Surface temp.	Sky temp.	Average
					Direct	Indirect	Total						
1950	hm	lys/min	kcal/m²hr	kcal/m² hr	kcal/hr	kcal/hr	kcal/hr	°F	°F	kcal/hr	°F	°F	°F
July 20	09 40			1060	265	90	355	100	111.2	202			
25	08 15	0.88	528	728	182	80	262	86	105.4	117	119	67	93
25	14 25	1.12	672	528	132	124	256	101	118.8	154	135	87[e]	111[e]
28	16 00	0.72	432	608	152	81	233	108	116.0	171	120	68	94
29	13 25	1.28	768	676	169	127	296	112	114.6	213	127	50	89
29	14 10	1.19	714	664	166	119	285	112	114.8	209	127	58	93
30	13 00	1.36	816	732	183	110	293	101	115.2	174	125	60	93
31	13 15	1.28	768	588	147	147	294	117	111.2	230	131	71	101
Aug 1	12 15	1.53	915	952	238	119	357	113	109.0	248	117	81	99
2	13 30	1.24	744	532	133	148	281	111	114.3	204	127	68	98
2	13 55	1.22	732	564	140	138	278	108	114.1	193	121	67	94
3	12 15	1.35	810	956	239	74	313	109	115.0	211	129	63	96
4	12 55	1.28	768	844	211	74	285	101	112.5	172	123	65	94
5	13 45	1.12	672	792	198	89	287	101	108.1	172	115	49	82
7	14 45	1.03	618	700	175	113	288	102	114.8	176	120	67[e]	94[e]
8	14 10	1.19	714	704	176	100	276	106	110.1	183	110	58	84
9	13 40	1.18	708	724	181	93	274	112	117.9	206	108	53	81
12	13 40	1.17	702	644	161	124	285	106	112.8	188	124	49	87
13	14 00	1.09	654	664	166	112	278	106	114.3	187	124	58	91
Average								106	113.2		122	63	93

[a] This is essentially Table 8 of *Sissenwine* and others [1951]; published with the permission of the Regional Environments Research Branch, Environmental Protection Research Division, Quartermaster Research and Development Center, U. S. Army, Natick, Mass.

[b] Interpolated from observations usually made within ½ hour of the Panradiometer observation.

[c] Assuming that man exposes a spherical surface of 1 m² to radiation, that his emissivity for solar radiation is 0.5, and his emissivity to radiation exchange with his surroundings is 1.0.

[d] Time at start of observation requiring about 20 minutes. Apparent local (sun) time is six (6) minutes later than Pacific Standard Time.

[e] The Sky Temperatures appear inconsistently high with regard to other temperatures preceding and following these observations on the same day.

with the radiometer directed as close to zenith as possible without including direct sunlight. It is seen that the sky temperature in this region, so measured, averaged about 50°F lower than the air temperature, while the soil surface temperature was about 10°F higher than air temperature, and the average radiant temperature, weighting surface and sky equally, was then about 20°F lower than the average air temperature of about 113°F. However, the radiant temperature of the surroundings as measured by the Panradiometer, a non-directional instrument, was only about 7°F lower than air temperature and may be of interest to the authors in comparisons with their values obtained with the Globe thermometer. In any event, the information contained in this report in its entirety should be of value in providing much comparative data particularly since the Eppley pyrheliometer was used in both studies and thus provides a common point of reference for correlating data from several different instruments.

The authors are to be commended for their contribution to this phase of climatology in which data in a form suitable for practical biological applications is at present sparse, scattered and largely uncorrelated with either animal or human thermal exchange.

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F. A. Brooks and *John R. Goss* (Department of Agricultural Engineering, University of California, Davis, California; received Nov. 1, 1957)—It seems proper to point out why the authors did not find good agreement between calculated and observed sky temperatures when using the values of *Goss* and *Brooks* [1956] and *Anderson* [1952, p. 92] for the constants in Brunt's empirical nocturnal atmospheric radiation equation.

The data presented in Figure 5 were obtained during the daytime with the Gier and Dunkle *directional* radiometer pointed at the north sky at a 60° angle above the horizon which is nearly the coldest spot in the sky hemisphere. The values for Brunt's constants reported by Goss and Brooks and by Anderson were obtained from data recorded with the Gier and Dunkle total *hemispherical* radiometer during the nocturnal hours in the absence of short-wave radiation. It is presumed that the authors did not correct their data presented in Figure 5 for scattered, incoming short-wave radiation, although this correction would be small since the Gier and Dunkle directional radiometer has a diaphragmed aperture half angle of only eight degrees.

The equivalent sky temperatures observed by the authors (under clear skies) are therefore lower than if based upon the total incoming atmospheric radiation from the upper hemisphere, and hence call for a smaller value for a in Brunt's equation. Furthermore, since the authors used current vapor-pressure readings throughout the day, a greater variation in b would be expected than for vapor pressures measured only when convective turbulence was fully developed.

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C. F. Kelly (Department of Agricultural Engineering, University of California, Davis, California), and *T. E. Bond* (Agricultural Research Service, U. S. Department of Agriculture, Davis, California; Authors' closure)—The authors appreciate very much the constructive comments on the paper by both Miss Stoll, and Goss and Brooks. We hope that the net result of the paper and discussions will be to make both meteorologists and engineers more aware of the possibilities in cooling, as well as heating, by exposure to the sky in the proper manner.

Miss Stoll's data for Death Valley are very interesting. The comparison with Imperial Valley is probably not as direct as suggested, because of the greater humidity in the Imperial Valley during the hot summer months, caused by southerly winds bringing in large amounts of moisture from the Gulf of California, and to the irrigation in the valley. The reason for our work in this area is to promote the raising of livestock. The main hindrance to summertime feeding of beef cattle and to dairying has been the drop in rate of gain or of production in the summer. It was early in our studies that Ittner, the livestock specialist of our research team, decided that the high night temperatures did not give the animals an opportunity to cool off as a preparation for living through another hot day. The reason for the high night temperatures is the blanket of relatively moist air over the area. In this respect Imperial Valley differs from a true desert climate. This also, we believe, explains why we obtained differences between daytime air and sky temperatures of 20 to 30°F, while Sissenwine's data indicates an average difference of 50°. It would be interesting to see how these temperatures respond to Brunt's equation, if vapor pressure data were available.

All comments by both Miss Stoll and Goss and Brooks are well taken, and we hope that their discussions will clarify our results adequately.

Discussion of "The Accuracy of Wind-Speed Estimates at Sea"

BY CHARLES F. BROOKS AND ELEANOR S. BROOKS

[*Trans.*, **39**, 52–57, 1958]

G. Verploegh (Koninklijk Nederlands Meteorologisch Instituut, De Bilt, The Nederlands)—Investigations into the various factors which influence Beaufort estimates of the wind force at sea are known to have been made on the basis of data of a variety of vessels with and without sail, moving ships and light-vessels. The authors have augmented this list with another set of original data which may be welcomed especially since it is the first time that routine observations of ocean weather ships were used for that purpose. According to the title of their paper the accuracy of the wind-speed estimates was their main object of investigation.

Now the word 'accuracy' is a rather dangerous one especially when it is used in a qualitative sense without mentioning in what respect and for which purpose the data are to be considered as accurate or not. When the authors state that "nevertheless, anemometer speeds are *obviously* (italics mine) more accurate than estimates from sea disturbance and may be used with some assurance for determining the errors of the latter" not only do they express a certain feeling rather than an established fact, but also they give an unusual and very specific meaning to the words 'accuracy' and 'error,' since by an error they mean a deviation of an estimated value of the wind speed from the speed measured at a height of 20 to 30 m above the sea surface. All factors which may bring forth this deviation are thus considered as sources of the 'error' of a wind-speed estimate at sea. Indeed, from this point of view anemometer speeds are obviously more accurate than estimates; however, from a statistical point of view one is equally free to take the estimated values as fixed and consider the deviations of the measured speeds as 'errors' of the latter.

In general the expressions 'accuracy' and 'error' should be confined to the deviations of a measured quantity with respect to the value which is sought by the measurement.

By this critical comment on the use of the words 'accuracy' and 'error' I have not meant to question the validity of the data presented by the authors. On the contrary, they are indeed of much value as an independent confirmation of earlier findings, some of which still needed such confirmation. To my opinion these data might, however, better be viewed in the light of the following scheme.

Both in synoptic meteorology and oceanography the wind speed to be observed on a routine basis has to be defined for a given level above the sea surface. International agreement has settled upon a level of ten meters; now let v be the wind speed at this level and B its equivalent Beaufort number. The conversion of B into v may be expressed as

$$f(B) = v \qquad (1)$$

In general (1) will not be satisfied by the individual observations. We may distinguish

(1) An error ΔB made by the observer when estimating the wind force. These errors may in the first-place result from individual differences of judgment, giving a standard deviation of the observations with respect to the mean of about 0.4 Beaufort (1.5 knots), a value which is confirmed quite well by the observations made by C. F. Brooks personally and mentioned also in the paper. The error ΔB may also originate from 'external' factors such as, for instance, the effect of strong currents on the appearance of wind waves or variations of the plankton concentration in certain areas [*Seilkopf*, 1956], or at changing winds as the authors were also able to demonstrate. These

errors may occasionally amount to about one Beaufort unit and in exceptional cases, for instance over unexpected, very strong sea currents, even to two Beaufort units.

(2) An error Δv in the anemometer reading. If the anemometer is properly exposed (which is still a rather difficult problem on board of a ship) we may assume that the errors resulting from the disturbance of the air flow by the ship itself and from the pitching and rolling of the ship are comparatively small, that is, the error distribution might have an estimated standard deviation of about one to two knots [see, for instance, *Sanuki* and *Kimura*, 1953]. If the wind speed is measured at a height of about 20 to 30 m above the sea surface the vertical velocity gradient will also contribute to a deviation with respect to the wind speed at ten meters. This gradient is highly dependent on the stability of the air layer involved and especially under stable conditions large deviations amounting to five knots or more may be found. Direct measurements of this gradient in relation with the thermal structure of the air have been made by various investigators; as a classical example of a large velocity gradient I may recall the case of a sailing ship which was driven for hours through a flat sea at six knots' speed with the wind only blowing into the top sails (Ann. Hydr., 1911, p. 576).

(3) An error will also be introduced by the use of a wrong conversion table. As long as the observers are allowed to estimate the wind force in Beaufort numbers the conversion into wind speeds in m/sec or knots will only be the concern of the meteorologist receiving the report and will not interfere with the estimate itself. But when the observers are asked to report the wind speed directly in knots, that is, in units which apparently are too small for a practical estimate, they will naturally tend to round off their estimates to easy numbers as the authors have demonstrated very clearly. If then a wrong conversion table is used systematic errors will be introduced. I think it is important to add this conclusion to the findings of the authors. The use of a wrong conversion table may provide another source of systematic error on board ships that are also equipped with an anemometer. On these ships the observers naturally tend to check their estimates afterwards with the readings of the anemometer 'just to be sure'; after a while the Beaufort estimates will become modified according to the conversion table used. It is therefore not surprising that the authors found a close agreement of the equivalent speeds as computed from the routine observations of the ocean weather stations with the present international scale. If, for instance, the international scale of 1926 were still in use, then, most likely, an agreement with these earlier equivalent speeds would have been found.

From this short review of the magnitude of the errors ΔB and Δv we may conclude that, since the Beaufort estimates relate to some average wind speed of the lower air layers and since, in general, direct measurements of the wind speed on board ship cannot properly be made at a level below 20 m, the accuracies obtained by both methods of determining the wind speed at ten meters are of the same order of magnitude, the standard error being in both cases about two knots.

Thus Beaufort estimates from sea disturbance may be considered about as accurate as wind-speed measurements made at a height of 20 meters or more above the sea surface.

There is another point which needs clarification. The authors have demonstrated a certain dependence of the observed differences between estimates and speed measurements on the thermal structure of the air as represented by the difference of air and sea temperature.

In a discussion on this effect much attention was given to the possibility of the observers being influenced by the somewhat different roughness and steepness of the waves raised by winds in a cold or a warm air mass. The authors concluded that 'warm winds over colder sea tend to be underestimated and vice versa.' Here again we must be very careful to interpret the word 'underestimated' rightly. If is meant underestimated with respect to a wind speed measured at a height of 20 and 30 m I agree, but when considered in its usual meaning, that is, with respect to the actual wind speed at ten meters, I object to this conclusion.

The observed correlation might be caused by two effects, that is, by differences of the vertical wind-speed profile above cold or warm water and by the above mentioned effect on the estimates. The question is which of the two effects is the most important one.

In order to find an answer to this problem I investigated the data of two Netherlands lightvessels on the possible existence of the latter effect [*Verploegh*, 1956]. Now on board these lightvessels the exposure of the anemometers was such (7 m), that a difference of the vertical wind-speed profile in dependence of the thermal air structure would hardly be perceivable when comparing the estimates and the measured wind speeds.

The absence of any correlation between the wind-speed differences on one hand and the air-sea temperature differences on the other led me to the conclusion that, if the observers really were influenced by differences of the wind waves in relatively cold or warm water, the effect on the estimates would still be too small to be detected in routine observations. That is the reason why I think that the correlation found by the authors on the basis of wind data measured at a height of 20 and 30 m refers mainly (if not wholly) to the differences of the vertical wind-speed profile and that we perhaps do better not to describe deviations of this kind as errors of the wind-speed estimates.

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VERPLOEGH, G., The equivalent velocities for the Beaufort estimates of the wind force at sea, *Kon. Ned. Met. Inst., Meded. Verhand.*, **66**, 1–38, 1956.

Eleanor S. Brooks (c/o E. L. Stabler, Golf Club Road, Greenwich, Connecticut, Author's closure) —I agree with Verploegh that a comparison of the accuracy of wind-speed estimates and measurements at sea is difficult, because as our paper states, "We have no standard true wind speed such as might be obtained from a fixed anemometer. We are comparing winds at different levels using two methods subject to different types of error." Our opinion that wind speeds obtained from anemometers are more dependable than those estimated from sea disturbance is, I believe, generally held. Otherwise, why should anemometers be installed on weather ships and large merchant ships?

The sea surface used as a wind-speed indicator might be likened to an anemometer with a large lag effect. This is apparently a frequent source of difficulty in making estimates. Taking our instances in which estimated Beaufort was below the measured value, we found increasing winds in slightly more than half the cases. Conversely, when estimated Beaufort exceeded measured Beaufort there were decreasing winds 70 pct of the time.

Verploegh suggests that estimates of wind speed are likely to follow too closely the anemometer measurements when both are made on the same ship. The systematic differences cited above show some independence between the two sets of observations.

When the data were obtained for our study, the observers were asked to make their estimates of wind speed from sea disturbance directly in terms of the Beaufort scale. As Verploegh says to have attempted estimates in knots would have been quite impracticable. The paragraph in our paper (p. 54) referring to the rounding off of figures recorded in knots, applied to anemometer data, not to estimates, and apparently was misinterpreted by Verploegh. I regret any ambiguity.

The effect of sea-air temperature differences on the vertical temperature distribution and wind-speed profile, and consequently on the height and steepness of waves has been described and measured by H. U. Roll, R. G. Fleagle, and others whose work is cited in our paper. The observer will necessarily be influenced by the character of the waves, as they are the basis of his estimate of wind speed. Hence this seems to me all part of one effect and hardly to be separated into two. I would agree with Verploegh that the effect is more marked when the anemometer is high above the sea surface. In his series of observations (1956) the anemometer was below the standard height for Beaufort conversion, in ours, above.

Discussion of "Correlation of Rainfall Intensity and Topography in Northern California"

BY RAY K. LINSLEY

[*Trans.*, **39**, 15–18, 1958]

W. T. Wilson and *D. M. Hershfield* (U. S. Weather Bureau, Washington, D. C.)—For several years investigators have faced the problem of deriving rainfall intensity-frequency values for regions where observations of short-duration rainfall are sparse or lacking. Our experience with synoptic, climatic, and topographic parameters has been that while parameters for slope, barrier

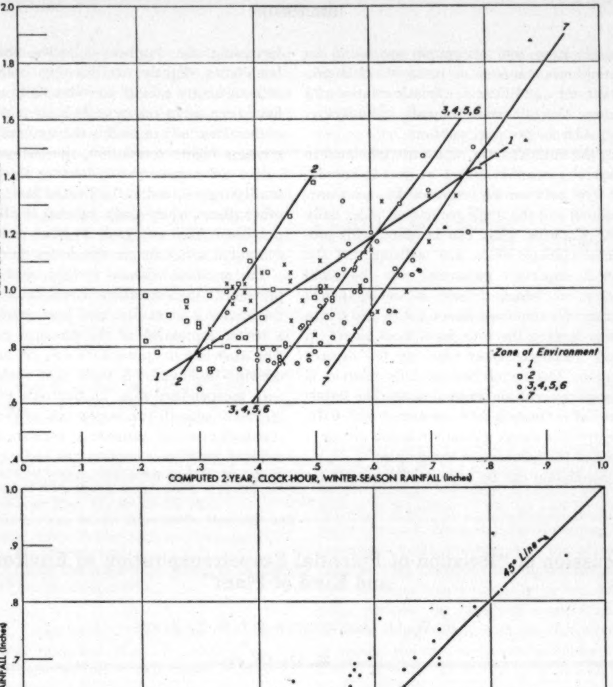

FIG. 3 – Relation between two-year, clock-hour, winter-season rainfall and index daily rainfall in four zones of environment in northern California

height, elevation, and orientation are useful for estimating mean annual or mean seasonal precipitation, they add little to climatic relations for estimating short-duration rainfall intensity-frequency, such as two-year one-hour.

Using the author's data, which are tabulated in the third reference of his paper, we found a correlation of 0.68 between winter-season two-year one-hour rainfall and the single parameter 'index daily rainfall.' Knowing what can be done with orographic or climatic zones, and realizing that the next most important parameter was the zonal parameter, we added it next in our graphical correlation. We combined Zones 3, 4, 5, and 6 into one zone, leaving the four zonal lines shown in Figure 3, which consumes relatively few degrees of freedom. The correlation for this relation is 0.83, compared with the author's 0.88. The standard error of estimate is 0.08, compared with 0.07. Apparently this simple climatic relation accounts for much of the influence of topography.

The correlation can be improved, of course, by increasing the number of zones, shifting their boundaries slightly, or drawing isolines of the ratio of hourly rainfall to index daily rainfall. We have been using two-year 24-hour rainfall instead of the index daily rainfall in the latter ratio. Besides giving a higher correlation, the two-year 24-hour values are necessary for defining the rainfall intensity regime; and in the United States and many other places where daily rainfall is observed and published, the two-year 24-hour value can be computed as easily as the index rainfall.

The question arises as to how much of the improvement in correlation would be a product of the analyst's ingenuity, and how much would be a better expression of the physical relationship. Any correlation up to 1.00 can be achieved by drawing isopluvials. A valid test could be made with independent data. In our own work we deliberately smooth the isopluvials so that the final standard error of estimate is consistent with the residual error of sampling, as determined from study of dense network data.

Discussion of "Relation of Potential Evapotranspiration to Environment and Kind of Plant"

BY W. O. DRINKWATER AND B. E. JANES

[*Trans.*, **38,** 524–528, 1957]

M. A. Kohler (U. S. Weather Bureau, Washington, D. C., received Oct. 23, 1957)—The authors cite the need for re-examination of methods because of inconsistencies and indicate that they have followed *Mather's* [1951] method of installing and operating modified evapotranspirometers. While it is stated that two plants were grown in each of the corn and celery tanks, no mention is made of tank size or how the number of plants was selected. It is believed that the results would have been quite different had one or three plants been grown in each tank. *Suomi* [1953] and *King* and others [1956] have shown that the effective area of an evapotranspirometer cannot be assumed to equal the actual area, even when great care has been exercised with respect to plant density.

It was of interest to note that the authors chose to derive solar radiation from black-minus-white atmometer values in preference to sunshine duration. Since the correlation analysis (Table 1) indicates that sunshine duration *per se* is the better index, radiation data derived therefrom [*Hamon* and others, 1954] would undoubtedly be superior.

The authors stress the advantage of 'natural periods' over arbitrary seven-day periods in correlation analysis, and cite an early paper by *Penman* and *Schofield* [1941] in support of this contention. Since the tanks were watered daily in this case, however, it is difficult to see the need for breaking the record into 'between-rain' groups. It is inconceivable that the correlation (measured versus computed PE) should increase from 0.40 to 0.97 by changing from seven-day to between-rain data, unless the total period PE was improperly used as the dependent variable instead of the mean daily PE. By this technique, one can demonstrate a high degree of correlation between two factors which bear no relation whatever on a daily basis. The spurious correlation results from the introduction of a third variable, the length of the period.

It is regretted that the basic data of Table 2 could not have been published in more detail.

Seasonal values (inches per day) cannot readily be compared when the period constituting the season changes from year to year. In the form shown, the data in this table appear inconsistent in numerous respects. For example, the relative black-atmometer evaporation in 1953 and 1954 is counter to what might be expected from any other type of data listed. All measured PE values in 1953 and 1954 exceed the actual Class A pan evaporation, which means they greatly exceed free-water (shallow lake) evaporation. Such values appear excessive in the light of energy considerations as applied to extensive, uniform areas.

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SUOMI, V. E., *Heat budget over a corn field*, Ph. D. thesis, Univ. of Chicago, 36 pp., 1953.

Edgar E. Foster (2232 Prune Ridge Ave., Santa Clara, Calif.; received Nov. 1, 1957)—The investigation reported on in this paper apparently indicates that there may exist a fundamental defect in the so-called energy-budget method of computing evapotranspiration and that the same defect exists in any method of computing evaporation from climatic elements. When the methods referred to are applied over a period of time sufficiently long so that averages are reasonably stable, the defect may not be important, but for short periods of time it does seem important. However, the change in relationship between evapotranspiration and heat, as indicated by the computed and observed values, from rain to rain, indicates that there exists another factor.

The paper does not make clear the effect of changes in soil moisture from time to time. This could make a difference. However, it seems that the experimentation would be conducted so that this would not be an important factor. Likewise, if it were, it seems that the agreement between computed and observed evapotranspiration would not coincide so regularly with the days of rainfall.

The one meteorological element not included in the energy budget (or analogous computation based on climatic elements) that would vary with the occurrence of rainfall is the humidity. The relationship between humidity and evaporation was pointed out many years ago by Dalton. This relationship has been retained in many common formulas proposed for computing evaporation, such as, for example, Rohwer's

$$e = 0.771\,(1.465 - 0.0186B)\,(0.44 + 0.118W)(e_s - e_d),$$

Where e = evaporation
B = barometric pressure
W = wind velocity
e_s = the vapor pressure of saturated air at the temperature of the water surface
e_d = mean vapor pressure of the air above the water surface

The energy-budget methods or methods based on climatic data do not contain a factor to account for the effect of humidity, that is to say, the difference in humidity of the air and its saturation vapor pressure. Since it is the difference between saturation vapor pressure and the actual vapor pressure that controls the evaporation and since this difference would normally be less during the rainy periods, the observed evaporation should be more in agreement with the computed, which is usually the case as shown in Figure 2. Therefore, it appears that this factor of humidity should be included in the method of computed evapotranspiration or evaporation.

Did the experiments include observations on humidity so that this viewpoint could be examined?

W. O. Drinkwater and *B. E. Janes* (Storrs Agricultural Experiment Station, University of Connecticut, Storrs, Connecticut; Authors' closure)—Kohler and others have indicated the effective area of evapotranspirometers is difficult to determine. For the grass tanks the actual area, 380 sq inches, was assumed to be the correct effective area. The height of the grass was maintained at about 1½ to 2 inches by clipping once a week. The rim of the tank, which was approximately ¼ inch thick, was one inch above the ground surface. The soil surface in the tanks was approximately the same height as surrounding area. The grass covered the rim of the tank so that it was not visible. The effective area of the tank for celery and corn is not necessarily that of the tank. The plants do not cover the entire area and portions

TABLE 3 – *Corrected correlations of measured PE (Unit I) with several climatic elements with data grouped into between-rain periods and seven-day periods*

Climatic element	Between-rain periods			Seven-day periods		
	1953	1954	1955	1953	1954	1955
Class-A pan evaporation	0.62[a]	0.55	0.38	0.51[a]	0.63[a]	0.90[b]
Black atmometer evaporation....	0.62[a]	0.56	0.23	0.59[a]	0.37	0.66
Solar radiation[c]......	0.42	0.70[a]	0.40	0.39	0.24	0.67[a]
Temperature (average)..	0.17	−0.23	0.64[a]	0.32	0.47	...
Sunshine (hr duration) .	...	0.72[a]	0.15	...	0.45	0.74[a]

[a] Significant at five per cent.

[b] Significant at one per cent.

[c] Derived from black minus white atmometers values, corrected.

of them extend beyond the rim of the tank. An attempt was made to have the same plant density in the tanks as in the surrounding areas, 12 inches apart for corn and six inches for celery. (Line 12, page 524 of paper should read: Two plants were grown in each corn tank and three plants in each celery tank.) This spacing was satisfactory for length of row. The rows in the field were spaced three feet apart. Each celery plant then occupied an area 6 × 36 inches or 216 sq inches. The area for each plant in the tanks was only 126 sq inches. The effective area for rainfall accumulation in the tanks was 380 sq inches but for absorption of radiation changed as the plants grew. When the plants were small the area of the tank was the effective area, however, as the plants grew the area of absorption of radiation increased. For the present study the area of the tanks was considered to be the effective area for both celery and corn.

The authors chose to use the difference in loss of water from black and white atmometers as a measure of solar radiation for two reasons. Duration of sunshine is based on an arbitrary standard of intensity above which point the Sun is shining and below which it is not shining. However, the atmometers are influenced by intensity of radiation and thus are more representative than duration. Atmometers are simple and inexpensive to operate making it possible for measurements to be made in a greater number of situations than duration which requires expensive recording equipment.

As suggested by Kohler, the correlation of PE and climatic elements grouped on a between-rain basis (Table 1) were incorrectly calculated. The correct values based on daily average values for the periods rather than totals for the periods are given in Table 3. The corrected values of r for the correlation between computed PE and measured PE based on between-rain periods were $r = 0.34$, -0.48 and 0.66, for 1953, 1954, and 1955 respectively. The 1955 value $r = 0.66$ was the only correlation which was significant. Changing the values used to plot the curves for between-rain periods (Fig. 2) from totals to averages also indicated a change from good to poor correlation. The corrected values indicate that relating PE measured from evapotranspirometers to climatic elements, there is little to be gained by grouping into between-rain periods. However, because of the value of between-rain periods in interpreting irrigation response, it would be desirable to use them in studying evapotranspiration phenomena in relation to irrigation.

Discussion of "Flood Frequency by Regional Synthesis"

BY R. ROBINSON ROWE, GORDON L. LONG, AND THOMAS C. ROYCE

[*Trans.*, **38**, 879–884, 1957]

Manuel A. Benson (U. S. Geological Survey, Washington 25, D. C., received Feb. 12, 1956)—This paper represents an unrestricted, though unmentioned, acceptance of the station-year method for annual-flood data. Experience shows that annual-flood peaks at gaging stations within even wide regions are not independent events, particularly for the higher peaks; hence the station-year method is apt to give misleading results. Note that the resultant regional curves shown in the authors' Figures 4 and 5 are to the right of the general positions of the individual frequency curves and do not represent the central tendency. This is due to (1) use of the station-year method, and (2) use of a straight line, which, at least in northwestern California (Fig. 4), disregards the curvilinear tendency of the individual records. The resultant curves may provide discharges which are too low for conservative design.

The combining of 12 station records, 15 to 45 years in length, to give 314 years of record, and the augmenting of this by means of a plotting-position computation which leads to a frequency curve defined up to 628 years, appears questionable to this writer. After all, only 45 years of flood experience are represented by the original data. Even were all the data spatially independent, there still remains a grave question as to whether the experience within a 45-year period can duplicate the pattern and range of experience within 628 years.

In the past the writer [*Benson*, 1952] has performed a statistical sampling test on a theoretical 1000-year flood record, with results comparable to those of the authors. The application of the unscrambling method to a composite curve as a test of homogeneity seems overly laborious and rather vague. The writer's study referred to above shows that chance sampling led to a spread (95 pct of the time) within roughly 25 pct of the mean value at any range. The authors' sample curves, Figures 2 and 3, appear to confirm this, and the 25 pct spread would appear to be a satisfactory simple criterion for homogeneity.

In the Sierra Nevada study the authors used the California plotting position, $T = Y/M$; in the other, they used the Hazen plotting position, $F = Y/(M-\frac{1}{2})$. The latter was done in order to offset the 'upward bias' introduced by the December 1955 flood. The selection of plotting positions appears to be too subjective and this procedure, at least, should be standardized.

The writer agrees with the concept of defining regionally applicable composite curves. However, the use of the station-year method should be restricted to events known to be independent. In general, for annual peaks, combining so as to produce a median curve better defining the general relationship during the period of record is more often warranted than combining end-to-end so as to produce an artificially long period of time.

Incidentally, the position of the northwestern California curve on Figure 6 does not agree with that on Figure 4.

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BENSON, MANUEL A., Characteristics of frequency curves based on a theoretical 1000-year record, U. S. Geological Survey, open file, 21 pp., August 1952.

Ray K. Linsley (Stanford University, Stanford, Calif., received Feb. 19, 1958)—A number of recent papers have treated the subject of flood frequency and especially the synthesis of regional frequency curves. The writer is well aware of the limitation of frequency analysis but some aspects of this most recent paper bear closer scrutiny. The authors present a concise explanation of the uncertainties of current plotting position formulas especially as they relate to the higher floods of a series. Their own table (p. 880) shows that the odds are roughly two to one that the highest flood in a series has a true return period longer than that given by conventional formulas. They then take actual frequency plots and draw so-called 'bilinear graphs' in an attempt to fit curves as closely as possible to the plotting positions which they have criticized. They justify this on the basis that there are two 'populations' in the flood series being sampled. If there are two populations these should be explicitly defined and the data separated on a logical basis into the two series before frequency analysis.

In the California mountain regions it is conceivable that two populations can be defined and studied separately. One would result from rain floods such as that of December 1955. The other population would consist of snow-melt floods which enter the annual flood series only in years when there are no significant rain floods. It should be relatively simple to recognize these two types in the record and then prepare the two distinct series required. It is quite possible that either or both of these series will also plot with a 'dog leg' and that in the majority of the cases the dog leg will break upwards since, as already noted, the odds are in favor of having floods in the series with true return periods greater than that by conventional plotting formulas. If so, it is hard to accept the argument that the frequency curve must be drawn by eye through the plotted points. Is it not better to make the most of all the data by fitting a statistical function than to allow the few high points, which are most likely to be in error, to determine the location of the curve?

As a test of homogeneity the authors develop a synthetic scatter pattern of frequency curves and propose that if the scatter among a group of curves plotted from actual flood data on several basins is "not greater than the chance distribution, the stations may be treated as homogeneous."

Is this a valid test of homogeneity? Is it fair to say that because two frequency curves do not diverge by more than the scatter in a chance sample that the basins are in fact homogeneous? Is it not possible that some of the differences between the several curves on Figures 4 and 5 are real differences? It seems quite reasonable to the writer to suppose that they are. There is a vast range in basin size and shape, a considerable difference in topography and mean annual rainfall, and a variation in mean elevation. This latter factor has a significant effect on the flood characteristics of a basin by controlling the portion of the total basin area contributing runoff from rainfall during a storm. In addition, many of the streams are regulated by reservoirs which may substantially affect the lesser floods. The effect of area alone can be very significant. The smaller basins will produce their maxima from relatively short, high-intensity rains, while the larger basins require a large total volume of rainfall to produce major floods. A small basin can be expected to receive at some time a higher average rainfall than a large basin will ever get, all controlling factors being equal. Since the relation between rainfall and runoff is curvilinear, greater depths of runoff should be anticipated during extreme floods on smaller basins than on the larger basins. Because, however, the paths of storms are more or less randomly distributed a small basin does not get the maximum rainfall in all storms and thus will produce many annual floods of no greater relative magnitude than those on the large basin. One might expect a steeper slope to the frequency curve of the small basin. The use of flood ratios instead of actual peaks will not mask this effect nor the effect of other factors which determine the flood producing characteristics of rivers. A test of homogeneity must rest on more than comparison with a synthetic chance sample. It should attempt, at least, to consider the physical features of the basins concerned.

The summation of a number of short records into a long record is the station-year approach which was suggested for rainfall data by the *Miami Conservancy District* [1936] and has since been substantially disqualified [*Hafstad*, 1942]. A significant problem here is the question of independence of the records which are combined. The data presented by the authors include a group of basins in close proximity and all basins in the group are affected simultaneously by a large general storm. Indeed, they even include more than one station on the same river. The error here is obvious if one considers the situation of combining only three stations on the same stream (for example, Kings River, Fig. 5). If there are 20 yr of record at each station and the highest peak at all stations occurred during the same flood, this flood is automatically assigned a return period of 60 yr at one station, 40 yr at the second, and 20 yr at the third (using $F = Y/M$).

In their conclusion the authors state "... in the extrapolation of frequency graphs for peak discharges large errors can be reduced by combination of non-dimensional flood ratios of several streams into one synthetic record." The proof for this is supposed to lie in Figures 4 and 5 but these figures show only a group of individual basin frequency curves with considerable scatter and a single synthetic curve. The writer can find no proof presented that the synthetic curve is any more reliable than the individual curves. It might be suggested that we should not attempt to extrapolate frequency curves substantially beyond the record length. If extrapolation of short records is necessary, there are available reasonably sound hydrologic procedures as outlined by *Kresge* and *Nordenson* [1955] and *Paulhus* and *Miller* [1957].

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PAULHUS, J. L. H., AND J. F. MILLER, Flood frequencies derived from rainfall data, *Proc. Amer. Soc. Civ. Eng.*, **83**, sep. 1451, 1957.

David M. Hershfield (U. S. Weather Bureau, Washington, D. C., received Mar. 14, 1958)—The authors have tackled the important hydrologic problem of flood frequency analysis with the purpose of improving the flood frequency estimates of individual streams by making use of all the data in a 'climatically homogeneous' region rather than short single station records. Although the problem of short-record estimates occurs frequently, it is a mockery to tell the design engineer that his sample is too small for reliable estimates. The engineer, as the authors have done, might resort to some form of regional analysis in an attempt to improve the quality of the estimates. However, if this problem is not recognized as a

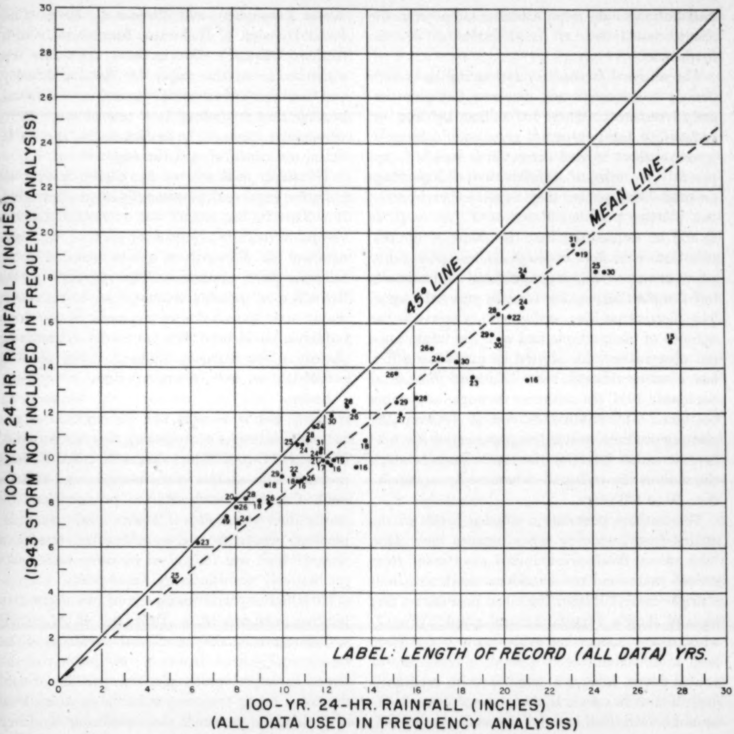

FIG. 7 – Comparison of 100-year 24-hour rainfalls for stations in the Los Angeles, Calif. area

statistical one, the predictive value of the results are vulnerable to serious criticism.

Because of the statistical nature of the problem, the important condition of independence must be met; that is, each extreme is independent of the other extremes. This condition is closely approximated for distributions at individual stations where each of the extremes (maximum annual values) represents the extreme of a large number of independent observations of the variate. When all the extremes or statistics based on these extremes are combined to form one long-record synthetic distribution, the condition of independence is violated if some of the observations are the result of the same event.

The combining of large rainfalls associated with the storm of January 1943 in Southern California is an example of improper grouping of observations from a number of stations in a 'climatically homogeneous' region. Of the records for the 50 stations analyzed in the Los Angeles, Calif., area (approximately 5000 sq mi), 33 had maximum annual 24-hour values associated with this one storm. The maximum annual values for the other 17 stations were associated with other storms. Figure 7 illustrates the effect that this one event has on the frequency distribution. The 100-year values were computed analytically by the *Gumbel* [1941] procedure using all the data and then omitting the 1943 rainfall. Combining all the data into one distribution would mean a biased sample and the result would be an underestimate of the frequencies.

The authors' method for estimating the return periods is subjective and, in some ways, not exactly consistent. They fit a line by eye on probability paper (type not given) and arbitrarily ignore outliers or give them "little weight." Apparently, in order to straighten out the plottings on probability paper, they vacillate between the two plotting positions Y/m and $Y/(m - \frac{1}{2})$. It should be emphasized that the shape of the distribution or the slope of distribution on probability paper changes with, say, additional observations, but the plotting-position formula stays the same. The plotting position $m/(n + 1)$ where n is the number of observations and m is the rank when the observations are plotted in ascending order, has a more rational basis [*National Bureau of Standards*, 1954] than either of the authors' plotting positions. The relative differences between the plotting positions used in this paper and $m/(n + 1)$ become rather large for the return periods which the authors are trying to determine by extrapolation, 30 to 100 years.

The authors postulate a dog-leg break in the annual-flood frequency series because they claim "the annual floods are a mixed assortment from several causes and not a random assortment from a single cause." Rather than just postulate a dog leg and show a "typical bilineal graph" (Fig. 7) without any supporting evidence, it would have been more convincing to present a few series of annual floods, selected at random, with each flood identified as to cause. If the cause of these floods cannot be identified exactly, or even dichotomized, there is obviously no basis for attempting to separate the floods in a frequency analysis. In the statistical analysis of extreme events, all that is needed are the magnitudes of the events (annual floods) which have been obtained by a systematic sampling procedure. The cause of the events does not enter into the frequency analysis. If, however, the cause is known, the annual floods can be symbolically identified on the probability paper.

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R. Robinson Rowe (California Division of Highways), *Gordon L. Long* (California Department of Water Resources), and *Thomas C. Royce* (California Division of Highways, Sacramento, Calif.; Authors' closure)—The authors appreciate the attention given this paper by Benson, Linsley, and Hershfield. Much of the discussion was critical, proving that hydrology is a science with many viewpoints; those of the hydrographer, the statistician, the educator, and the engineer.

The paper was written by engineers with an objective expressed purposefully in the introduction. Since its importance was overlooked and the viewpoint requires rejection of most of the arguments of the discussors, it will be repeated in the following brief statement. The objective is the derivation of reliable estimates of 10-yr, 30-yr, 50-yr, and 100-yr momentary-peak floods from published basic flood data for use in determining clearances for highway bridges. Policy inhibits overdesign as well as underdesign.

Benson calls the procedure the 'station-year method,' but it is more like the 'method of obtaining relation for frequency for all streams' [*Fuller*, 1914, p. 580] and should be called Fuller's method. The station-year method was Fuller's method applied much later to precipitation. He warns that treatment of higher peaks as independent events may give misleading results, a hazard which was recognized by using such peaks qualitatively to ordinate the lesser peaks.

He criticizes discretionary use of two alternative plotting positions ($F = Y/M$ and $Y/(M - \frac{1}{2})$) and disregarding the 'curvilinear tendency' of the former on Figure 4. It was not the purpose of the paper to argue which plotting position should develop a linear frequency relation on which kind of probability paper. If the curvilinear tendency is real, the paper or plotting formula is wrong, but the procedure is correct for the objective. Probably the curvilinear tendency is an illusion caused by the infrequency of the 1955 floods.

Benson's unpublished corroboration of random statistical sampling should be noted. If all hydrologists would take the time and trouble to run such a sample just once, they would appreciate the sobering fact that a single historical frequency series is a poor measure of future events. Similarly for the test of homogeneity; once done, the picture of 25 pct spread will suffice for future tests, as he says.

His preference for combining frequency charts laterally into a median curve instead of longitudinally into an artificially long period is difficult to understand. If some events are dependent, both methods overweight them. Median (or mean) curves would not properly weight long records more than short ones.

He correctly points to an error in plotting Figure 6. As this was intended to compare two slopes qualitatively, it is not being revised.

Linsley criticizes the bilinear graphs and claims that it should be relatively simple to separate the two populations so combined. This is not true. Snow-melt floods can be identified; in fact they have been excluded from Figure 5, but dog legs remain. The other set (Fig. 4) is not sensitive to melting snow. To eliminate the remaining dog legs, it would be necessary to (1) define the dominant storm, (2) identify and exclude peaks from recessive storms, (3) replace the excluded peaks with lesser peaks from storms of the dominant type. Even if possible, these substitutions would require a great deal of research, particularly in early records for which only one peak was published for each year.

His objection to the bilinear graph is that it prohibits an analytical calculation of the frequency curve. The paper described a visual fitting of the curve, ignoring the undefined lower limb. Linsley protests that this gives too much weight to high points plotted with unavoidable large errors, but step (8) on page 882 said explicitly, "determine visually a best-fit line for the well-defined part of the graph, giving little if any weight to wild points at the infrequent end." The danger of indiscriminate statistical analysis is the lack of discretion in the method of least squares. Visual methods are preferable and sufficiently accurate, considering the large error inherent in each item of the basic data.

Linsley's questions on homogeneity derive from lack of a definition. Statistically it might be defined as coincidence of non-dimensional frequency curves. By that definition, Elm Creek in Alabama, and Oak Creek in California might happen to be homogeneous, although dissimilar in all other respects. However, even if there is a hydrologic law of nature that all such curves are straight lines on a certain probability paper, definition of the curves from available data is only approximate. Our paper described a test for homogeneity which is really a negative test for heterogeneity. If not excluded by the test, "the stations may be treated as homogeneous," even though homogeneity is only approximate, at best.

He is correct in supposing that some of the differences in the station plots of Figures 4 and 5 are due to climate and terrain rather than chance. But if differences of the two kinds are inseparable, charging all to chance may give more reliable results than charging all to nature. For example, note the station curve on Figure 4 for Scott River (No. 7). Extrapolation of an ordinary frequency curve to 100 yr would give $6Q_5$, instead of $2.4Q_5$ by regional synthesis. Fact, if it could be known, is probably between these two, but the authors contend that regional synthesis gives the more reliable estimate for bridge design.

Most of his suggestions for qualitative tests of homogeneity were considered in the preliminary definition of the region. In particular, the records are practically unregulated, but it is interesting to note that artificial regulation can produce frequency curves with two dog legs, so that some angularity of other curves may be due to natural regulation.

Linsley's statement that the station-year approach has been substantially disqualified is not supported by his reference. It would be more appropriate to say that Hafstad qualified the method by proposing a measure of accuracy based on statistical dependence. Her conclusions were challenged by several discussers. The method is still widely used.

He also questions independence of records on adjoining basins during a large general storm, particularly two or more records on the same stream. Absolute independence is neither claimed nor necessary, but dependence is far from absolute, too. Without some considerable degree of independence it would not be necessary to maintain so many gaging stations. As a measure of independence of stations in the same basin, note in Table 2 the six stations in the Klamath Basin (including Salmon, Trinity, and Scott Rivers). The 1956 flood is rated variously from 100-yr to more than 1000, while adjacent basins recorded only a 17-yr flood on the north and a 37-yr flood on the south.

Linsley decries lack of proof that the synthetic curve is any more reliable than the individual curves. In predictive hydrology there is no proof and none is offered. He suggests that two alternative procedures are "reasonably sound" without describing them as proved. The inconsistency is obvious. The alternatives are not sound for either region synthesized, since precipitation records are fewer in number and shorter in record than stream-gaging stations.

Hershfield concurs in the objective of the paper, but with misgivings over independence of observations of the same event at two stations. This has been answered, but can be restated by the paradox, 'sameness is relative.' He also concurs in disregard of cause of dog leg, but with some curiosity as to that cause. A digression might be interesting but not in point.

His analysis of 24-hr precipitation at 50 stations near Los Angeles to show the effect of bias is incomplete. Suppose he synthesized the data successively with and without the 1943 record. Wouldn't these two curves also diverge by about 20 pct? How does the alleged bias affect flood peaks on streams sensitive to shorter or longer storms?

Like Benson, he criticizes use of two formulas for plotting positions, charging erroneously "they vacillate." He suggests a third formula as more rational. It was not the purpose of the paper to revive this perennial argument, but to illustrate applicability of the method to any rectified procedure.

Summarizing, the discussion has called attention to error rather than mistake. Error of fairly large magnitude was admitted as a premise for systematic reduction. Criticism of use of dependent data was fallacious because (1) dependence is not absolute, and (2) error of exclusion might be greater than error of inclusion. Alternative procedures are less reliable for the objective in bridge design.

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Notes and Personalia

Notes

New Earth Sciences Program of the National Science Foundation—The National Science Foundation has announced the establishment of a Program for Atmospheric Sciences in the Division of Mathematical, Physical, and Engineering Sciences, with Earl G. Droessler as Program Director. Proposals for work in this field were formerly handled in the Program of Earth Sciences, of which William E. Benson is the Director. The new Program was established by special congressional action as a result of recommendations of the President's Committee on Weather Control and the Committee on Meteorology of the National Academy of

Sciences—National Research Council established especially to study this program.

Space Science Board of the National Academy of Sciences—A 16-man Space Science Board to survey in concert the scientific problems, opportunities, and implications of man's advance into space has been appointed by Detlev W. Bronk, President of the National Academy of Sciences—National Research Council. Lloyd V. Berkner, President of Associated Universities, Inc., and Vice President of the American Geophysical Union, has been named as Chairman. Others on the Board include: Harrison S. Brown, A. H. Shapley, John A. Simpson, Harold C. Urey, James A. Van Allen, Harry Wexler, and George P. Woollard. Hugh Odishaw has been named Executive Director. Eleven subcommittees have been established to carry on various phases of the work.

Books in the Earth Sciences Needed at the University of Chile—A new School of Earth Sciences is being established at the University of Chile in Santiago and an appeal has been made for books, journals, and other publications bearing on any aspect of this broad field. Prospective contributors should write to Dr. Pierre St. Amand, U.S.O.M. Chile, United States Embassy, Santiago, Chile, to make arrangements to have them shipped at no cost to the donor.

Catalogue of Active Volcanoes of the World—The International Association of Volcanology, IUGG, (Francesco Signore, Secretary, Via Tasso 199, Naples, Italy) announces the availability of Part VI of the Catalogue, Central America, compiled by F. Mooser, H. Meyer-Abich, and A. R. McBirney, at a price of $5.00. Parts I–V relating to (I) Indonesia, (II) Philippine Islands and Cochin China, (III) Hawaiian Islands, (IV) Africa, and (V) Melanesia, are also available. Send orders to the Secretary of the Association.

New Civilian Space Agency—A new law has been passed by the Congress establishing an official space agency combining this with the National Advisory Committee on Aeronautics, which has long been in existence. T. Keith Glennan, President of Case Institute of Technology, has been designated its Chairman.

Plans for Continuation of Igy—At a recent meeting of the International Committee for IGY (CSAGI), with participants from about 60 nations in attendance in Moscow, agreement was reached to continue the work of the IGY through 1959. This still requires the concurrence through financial appropriation of the governments of the various countries.

Availability of Bulletin of the International Association of Scientific Hydrology—This *Bulletin*, published four times a year by the International Association of Hydrology, IUGG, is now in its third year. The subscription rate is $3.00 for the four numbers. While this is published by the Secretariat of the International Association (L. J. Tison, Secretary, 61 Rue des Ronces, Gentbrugge, Belgium), subscriptions may be placed in the United States with Ralph N. Wilson, Secretary of the Section of Hydrology, AGU, at 3322 Stanford Street, University Hills, Hyattsville, Maryland. The *Bulletin* is a ready means for hydrologists the world over to keep up with current work in hydrology in the various parts of the world and includes reviews and news notes.

Availability of Bulletin Géodésique—*Bulletin Géodésique* of the International Association of Geodesy, IUGG, is now published by Pergamon Press and is available on subscription at the rate of $12.60 per volume. Individual subscribers certifying that the journal is for their personal use may subscribe at the rate of $5.60 per year. Send subscriptions to the Pergamon Press, 122 East 55th Street, New York 22, New York, or 4-5 Fitzroy Square, London W.1, England.

First Municipal Water-Desalting Plant to be Built—The first desalting plant for a United States city is to be built at Coalinga, California, this being a plant of 28,000 gallons per day and using an electric membrane. It will be built under contract with Ionics, Incorporated, of Cambridge, Massachusetts. It will increase the city's supply by 50 per cent of the separately distributed drinking and cooking water. It will be used to remove excess minerals from the city's plentiful but brackish well water.

Expanded Agricultural Weather Services for the Mississippi Delta Region—Arrangements are being completed to carry out a pilot agricultural weather-service project designed to provide farmers in the cotton belt of the Mississippi with more frequent and more detailed weather forecasts to meet problems during the growing season involving amounts and times of precipitation, the likelihood of heavy dew, the severity and duration of rain and wind storms, and the range of daily temperatures. The project will involve the establishment of additional cooperative observers, the assignment of additional forecasters to the Weather Bureau office at Jackson, Mississippi, the establishment of a special weather information teletype circuit, and the assignment of a professional meteorologist familiar with agricultural weather problems to work with the Delta Branch Experiment Station at Stoneville, Mississippi.

Conference on Physics and Medicine of the Atmosphere and Space to be Held November 10–12 in San Antonio, Texas—The International Conference on Physics and Medicine of the Atmosphere and Space will be held in San Antonio, Texas, November 10–12, 1958. It will be sponsored by the U. S. Air Force School of Aviation Medicine. Among those participating will be Joseph Kaplan, Chairman of the U. S. National Committee for IGY; Gerard P. Kuiper, Astronomer at the University of Chicago; James A. Van Allen of the University of Iowa, and Fred L. Whipple, Director of the Smithsonian Astrophysical Observatory. Interested persons should write to Southwest Research Center, 331 Gunter Building, San Antonio, Texas.

Establishment of Seismic Reference Service—T. A. Manhart, President of Century Geophysical Corporation, has announced that that company has joined with the Schlumberger Well Surveying Corporation to establish the Seismic Reference Service, which will provide the oil industry throughout the United States with a geophysical velocity logging service. Although Century Geophysical Corporation will continue its headquarters in Tulsa, the American headquarters of the new service are located in Houston.

Improved Hurricane Warning Service for East Coast and Gulf of Mexico Areas—The Weather Bureau has announced that the hurricane warning service of the Bureau has been strengthened considerably as a result of expanded observation networks, additional aircraft reconnaissance, better telecommunications, and other facilities. Much detailed knowledge on the behavior of hurricanes has been gained since the establishment of the Hurricane Research Project at West Palm Beach in 1955. During the voyages of the Coast Guard Cutter *Sebago* in the Gulf of Mexico, four specially trained observers will take surface and upper-air observations. Eight additional smaller Coast Guard cutters in operation in the Gulf of Mexico have new precision meteorological instruments aboard with specially trained personnel for their proper observation.

Personalia

JOHN N. ADKINS, Director of Earth Sciences of the Office of Naval Research, has been named Chairman of the Division of Earth Sciences, National Academy of Sciences–National Research Council, to take the place of Harry H. Hess.

HARVEY O. BANKS, Director, California Department of Water Resources, has recently been awarded honorary membership in the American Water Works Association.

DETLEV W. BRONK, President of the National Academy of Sciences, President of the Rockefeller Institute for Medical Research, and Chairman of the National Science Board, has recently been made a foreign member of the Soviet Academy of Sciences.

J. CL. DE BREMAECKER will be on leave from the Institute for Scientific Research in Central Africa starting in August 1958. He will spend one year at Dunbar Laboratory, Harvard University, on a research fellowship.

JAMES J. DOLAND, Professor of Hydraulic Engineering at the University of Illinois, has recently retired after 32 years with the University.

JOHN G. FERRIS, Research Engineer, Ground Water Branch, U. S. Geological Survey, has recently been presented a Distinguished Service Award by the Department of Interior.

ALBERT G. FIEDLER, Assistant Chief, Water Resources Division, U. S. Geological Survey, has recently been awarded honorary membership in the American Water Works Association.

LAURENCE M. GOULD, President of Carleton College, has been elected President of Phi Beta Kappa for a three-year term.

HENRY W. HEMPLE, Captain, U. S. Coast and Geodetic Survey, retired, has been named the recipient of the 1958 Distinguished Service Award of the Alumni Association of Illinois Institute of Technology. Prior to his retirement in 1952, Captain Hemple was Chief of the Division of Geodesy.

J. W. HIGGINS, who served as District Geologist in the Exploration Department of the Standard Oil Company, has been designated Senior Research Geologist of the California Research Corporation on Oil Field Research.

FREDERICK L. HOTES of the Development and Resources Corporation, Ahwaz, Iran, has been given the J. C. Stevens Award of the ASCE for his discussion of the paper "Ground-water development—basin recharge."

JAMES H. KRAAKEVIK, Head of the Research Section of the Atmospheric Electricity Branch of the U. S. Naval Research Laboratory, has accepted an appointment as Assistant Professor of Physics at Wheaton College as of September 1, 1958. He will retain association with the Naval Research Laboratory as a part-time consultant.

J. LAURENCE KULP, Professor of Geochemistry and Head of the Geochemistry Laboratory of Columbia University, will spend the coming academic year at Oxford University as a National Science Foundation Senior Postdoctoral Fellow.

WALTER B. LANGBEIN, Hydraulic Engineer of the U. S. Geological Survey, has recently been given a Distinguished Service Award by the Department of Interior.

LUNA B. LEOPOLD, Chief Hydraulic Engineer, U. S. Geological Survey, has recently received a Distinguished Service Award from the Department of Interior.

DELBERT M. LITTLE, Deputy Chief of the U. S. Weather Bureau, retired on July 31, 1958, after more than 41 years of service.

MARTIN A. MASON, Dean of the School of Engineering, George Washington University, has been appointed to the Board of the Engineering Foundation which was established in 1914 to foster research in the science of engineering.

JOHN L. MERRIAM has recently returned from two years of duty as Senior Irrigation Engineer for the Division of Water Resources in the Ministry of Agriculture of Saudi Arabia to take up duties as Associate Professor of Irrigation at California Polytechnic College at San Luis Obispo, California.

ROBERT M. PAGE has been named Director of Research for Electronics in the Naval Research Laboratory.

JAMES A. PEOPLES, JR., has left his work as Head of the Terrestrial Sciences Laboratory of the Air Force Cambridge Research Center to take up duties as Associate Professor of Geophysics in the Department of Geology of the University of Kansas.

BARNEY J. PETERSON of the U. S. Geological Survey, retired, has recently received a Distinguished Service Award from the Department of Interior.

SVERRE PETTERSSEN, Professor of Meteorology at the University of Chicago, has recently received a Gold Medal Award from the American Meteorological Society for his contributions to the analysis of atmosphere and weather conditions.

TROY L. PEWE, formerly Geologist-in-Charge of the Alaskan Geology Branch, U. S. Geological Survey, College, Alaska, has recently been appointed Head of the Department of Geology at the University of Alaska.

GEORGE L. PICKARD, Professor of Physics at the University of British Columbia, has been appointed Director of the Institute of Oceanography at that University, succeeding W. A. Clemens who served as Chairman of the Committee on Oceanography since 1949 and was appointed as the first Director in 1954.

ROGER R. REVELLE, Director of Scripps Institution of Oceanography of the University of California, has been named Director of the University's new Institute of Technology and Engineering, located at La Jolla, California.

William W. Rubey, Geologist, U. S. Geological Survey, has recently been given a Distinguished Service Award by the Department of Interior.

Pierre St. Amand has taken a position with the International Cooperation Administration to help start a new school of Earth Sciences at the University of Chile in Santiago. He notes that the library in science is very fragmentary and appeals for contributions to the library in almost any field of science, requesting any who have contributions to make to write to him (U.S.O.M. Chile, United States Embassy, Santiago, Chile) and he will make arrangements to have them shipped at no cost to the donor and inscribed with the donor's name if he desires.

Allen H. Schooley of the Naval Research Laboratory has been designated as the new Associate Director of Research for Electronics, succeeding Robert M. Page.

Paul B. Sears of the Conservation Program of Yale University was recently awarded an honorary doctorate by Oberlin College.

H. Burr Steinbach, experimental zoologist and general physiologist, serving as Professor and Head of the Department of Zoology at the University of Chicago, has been designated as Chairman of the Division of Biology and Agriculture of the National Academy of Sciences–National Research Council. He succeeds L. A. Maynard of Cornell University. In his new capacity he will be a member of the Executive Committee of the AGU.

H. O'Reilly Sternberg, Director of the Center for Research in Geography of Brazil, and Professor of Geography at the University of Brazil, will serve as Visiting Professor of Geography at Indiana University during the second semester of the academic year 1958–1959.

B. Sundara Rama Rao, Professor of Geophysics at Andhra University in India, has taken up duties with the United Nations as an expert in Geophysics under the UNESCO Technical Assistance Program. He has been assigned the task of organizing postgraduate teaching and research in applied geophysics at Rangoon University in Burma.

Max Suter, Principal Engineer of the Illinois State Water Survey, retired September 1, 1958, after 22 years of service with the Survey.

William F. Uhl, President, Chas. T. Main, Inc., has been awarded the Rickey Medal for contributing "in an important manner to the science or progress of hydroelectric engineering."

Ernest H. Volwiler, President and General Manager of Abbott Laboratories, has been named Chairman of the Division of Chemistry and Chemical Technology, National Academy of Sciences–National Research Council, to succeed Frederick D. Rossini of Carnegie Institute of Technology.

George D. Whitmore, Chief Topographical Engineer for the U. S. Geological Survey, has recently been presented a Distinguished Service Award by the Department of Interior.

Fritz Zwicky of Mount Wilson and Palomar Observatories was one of the recent winners of prizes for the best essays on gravity awarded by the Gravity Research Foundation.

Willie O. Byrd of Northrop Aircraft, Incorporated, died July 6, 1958, at the age of 51. He was born in Augusta, Georgia, and took his baccalaureate degree from the Georgia Institute of Technology in 1927. He began his professional career with the Georgia State Highway Department as an engineer and took up duties in 1929 with the Walton Flythe Engineering Company in Georgia. In 1934 he established his own consulting firm and became a county engineer in 1935. From 1936 to 1946 he was in the Maps and Surveys Division of the Tennessee Valley Authority. Subsequently he did work in Guam and with the Mapping and Charting Research Laboratory of Ohio State University until 1953. Since this time he had been a specialist in research and development of reconnaissance systems for Northrop Aircraft. He had been a member of AGU since 1949.

Albert C. Hornady, Consulting Geologist in Amarillo, Texas, died July 5, 1957, at the age of 57. He took his baccalaureate degree from the University of Nebraska in 1930 and his master's degree from the same school in 1932. He began his professional career with the Phillips Petroleum Company and became their District Geologist prior to the establishment of his own firm in 1950. He had been a member of AGU since 1947.

Robert Larimore Pendleton of Kasetsart University in Bangkok, Thailand, died June 23, 1957, at the age of 66. He was born in Minneapolis and took his baccalaureate degree from the University of California in 1914 and his doctorate in soils chemistry in 1917. While working for his doctorate, he was assocated with the Soils Survey of California. He began teaching duties at Ewing Christian College in India in 1918, and took up duties with the Director of Agriculture, Gwalior State, India, in 1919, becoming Director in 1921. He then devoted several years to the teaching of soil technology at the College of Agriculture of the Philippines, where he continued until 1935. From 1935 to 1942, he was with the Department of Agriculture and Fisheries of Siam. In 1942, he became Principal Soil Technologist for the Office of Foreign Agricultural Relations, U. S. Department of Agriculture, and worked on various assignments in the Belgian Congo, the Far East, and South America, serving also during a part of this period as Professor of Tropical Soils and Agriculture at Johns Hopkins University. He had been a member of AGU since 1942.

Special Announcements

BACK *Transactions* OF THE AGU—Under arrangements with Walter J. Johnson, Inc. (111 Fifth Avenue, New York 3, New York), the stock of back *Transactions* of the AGU for 1955 has recently been turned over to that company for sale. The volume is still complete. Issues earlier than 1955, many of them fragmentary, were previously turned over to this company, whose affiliated company, the Johnson Reprint Corporation, is undertaking the reprinting of out-of-print back numbers. The first twelve volumes, through 1931, are now available from the company and others are in progress, their completion depending in some measure upon the demand that develops for these. Persons interested in these issues should write direct to the company rather than to AGU.

MEETING OF THE PACIFIC NORTHWEST REGIONAL GROUP—The Pacific Northwest Regional Group will hold its annual meeting in Portland, Oregon, November 13–14, 1958. The program for this year is built around the central theme of the International Geophysical Year. A feature of the meeting will be an address by Lloyd V. Berkner, Vice President of AGU and Vice Chairman of the International Committee for the International Geophysical Year. Interested persons should get in touch with the Chairman of the Regional Committee, Wilbur D. Simons (U. S. Geological Survey, 529 Perkins Building, Tacoma 2, Washington) or V. P. Schermerhorn, Secretary-Treasurer (U. S. Weather Bureau, 320 Custom House, Portland, Oregon).

MEETING OF THE AAAS IN WASHINGTON, D. C., DECEMBER 26–31, 1958—It is the plan that the American Geophysical Union will co-sponsor appropriate programs in the meeting of the American Association for the Advancement of Science held between Christmas and New Year's in Washington. Specifically included are a symposium on the subject of water and agriculture and sessions relating to the IGY.

PACIFIC SOUTHWEST REGIONAL MEETING TO BE HELD AT STANFORD, FEBRUARY 5–6, 1959—Attention is again called to this meeting, and plans for the program are developing rapidly. The Regional Committee has recently added to its membership Warren S. Wooster of Scripps Institution of Oceanography and J. F. T. Saur, Jr., of Stanford University especially to represent the field of oceanography. The other members of this Committee are: Vito A. Vanoni, Chairman; R. Corday Counts, Jr., Secretary; Eugene N. Bollay; Robert E. Holzer; Harlowe M. Stafford; and David K. Todd. Persons interested in participating in the program are asked to get into touch with the Program Chairman, Joseph B. Franzini, Civil Engineering Department, Stanford University, Stanford, California.

FORTIETH ANNUAL MEETING TO BE HELD IN WASHINGTON, D. C., MAY 4–7, 1959—As announced in the August issue of the *Transactions*, the Fortieth Annual Meeting will be held in Washington, D. C., Monday to Thursday, May 4–7, 1959. Plans of the various Sections are now getting under way, and it is anticipated that all Sections will have meetings. Also, there will be general meetings of the Union as a whole, including a Smoker on Monday evening, May 4, a general evening session including the Award of the William Bowie Medal on Tuesday evening, May 5, and a general session on Wednesday afternoon, May 6. Suggestions with respect to any of the Section or Union meetings are invited. Suggestions for the Union meeting should be sent to Philip H. Abelson, Chairman of the Committee on Meetings, AGU, 2801 Upton Street, N. W., Washington 8, D. C. For information regarding Section meetings, see list of Secretaries and Program Chairmen below.

This announcement will also serve as an invitation for members and others to send word of plans for papers to be presented. Titles of papers with three copies of the abstracts should be sent in as soon as possible and not later than February 20, 1959. Please give information concerning the time required (most papers are allowed from 10 to 20 minutes) and the projection equipment needed. This information should be sent to the office of AGU at 1515 Massachusetts Avenue, N. W., Washington 5, D. C., or to the Secretary or Program Chairman of the appropriate Section, as follows:

Geodesy, Frank L. Culley, Army Map Service, 6500 Brooks Lane, Washington 25, D. C., or Donald A. Rice (Program Chairman), U. S. Coast and Geodetic Survey, Washington 25, D. C.

Seismology, James A. Peoples, Jr., Department of Geology, University of Kansas, Lawrence, Kansas.

Meteorology, Woodrow C. Jacobs, 3812 Nash Street, S. E., Washington 20, D. C., or Max A. Eaton (Program Chairman), Office of Naval Research, Washington 25, D. C.

Geomagnetism and Aeronomy, Robert E. Gebhardt, U. S. Coast and Geodetic Survey, Corbin, Virginia

Oceonography, Donald W. Pritchard, Johns Hopkins University, Baltimore 18, Maryland.

Volcanology, Geochemistry, and Petrology, Lyman T. Aldrich, Department of Terrestrial Magnetism, 5241 Broad Branch Road, N. W., Washington 15, D. C.

Hydrology, Ralph N. Wilson, 3322 Stanford Street, University Hills, Hyattsville, Maryland, or Bernard Frank (Program Chairman), 2807 Washington Avenue, Chevy Chase 15, Maryland.

Tectonophysics, Benjamin F. Howell, Jr., Department of Geophysics and Geochemistry, Pennsylvania State University, University Park, Pennsylvania.

As Section Secretaries reserve the right to close filled programs in advance of the dates indicated, please make it a point to send word in early. Abstracts of the papers are published in the program. Remember that an abstract is an opportunity to bring the important results of your work to all those that see the program. The abstract should be concise but comprehensive and informative, and must not exceed 200 words. Longer abstracts will be reduced to 200 words or omitted at the editor's discretion. Complete manuscripts are not necessary but are desired and should be forwarded to the office of the Union by April 15 so that they will be available for science news writers. Please indicate whether the paper is being submitted for the program only or also for consideration for publication in the *Transactions*. If a paper is written in collaboration, please indicate by whom it will be presented. Arrangements can usually be made with the Section Secretary or Program Chairman for the presentation of papers by authors who are unable to attend, but papers to be presented by title only are not included in the program.

Make hotel or room arrangements directly with the hotel of your choice at an early date. If you fail on the first attempt, bear in mind that advance bookings that are not taken up are cancelled two weeks in advance and that a follow-up request in mid-April may bring the desired response. We are making block bookings at three hotels again; an announcement regarding these will appear in the Special Announcements in the December issue of the *Transactions*.

ELECTIONS OF OFFICERS IN 1959—Nominating Committees of the Union and the Sections are to report to the Executive Committee on October 18, 1958, concerning their nominations for officers for the triennium beginning July 1, 1959. A list of the nominees will be published in the December issue of the *Transactions*. In accordance with the regulations set up, nominees by petition may be added during January. See the December issue for details.

PUBLICATION PLANS FOR 1959—The ballot concerning publication plans recently placed before the membership has been tallied, 2081 voting in favor of the changes, 78 not in favor, and 46 ballots void. Accordingly, plans are progressing rapidly to institute the new monthly journal beginning in 1959. P. H. Abelson, Director of the Geophysical Laboratory of the Carnegie Institution of Washington, and James A. Peoples, Jr., Professor of Geophysics, Department of Geology, University of Kansas, have been appointed Co-Editors. Your attention is called to the four-page insert at the beginning of this issue which shows the tentative cover of the first number of the new journal. The inside front cover also appears about as it will appear in the journal. The succeeding two pages give more information on the publication plans. The *Transactions* will continue as a quarterly in 1959, containing word of activities of AGU, notes and personalia, and quasi-scientific material. Your comments are solicited.

TITLE PAGE FOR 1958 VOLUME—The title page for the 1958 volume is being carried in this issue of the *Transactions* (rather than the December issue) just preceding the Table of Contents.

NATIONAL ACADEMY OF SCIENCES

Number 15 • September 1958

IGY BULLETIN

A monthly survey by the U. S. National Committee for the International Geophysical Year. Established by and part of the National Academy of Sciences, the Committee is responsible for the U. S. International Geophysical Year program in which several hundred American scientists are participating and many public and private institutions are cooperating.

The ARRL-IGY Propagation Research Project

This report is based on material supplied by Mason P. Southworth, ARRL-IGY Project Supervisior

Long-range, short-wave radio transmissions depend on conditions in the ionosphere, an electrified region of the atmosphere extending from approximately 45 to 250 mi above the earth's surface. The ionosphere contains several semi-permanent ionized layers which reflect most radio waves having wavelengths between 10 m and 10 km. Multiple reflection of a radio signal between ionospheric layers and the earth makes long-distance short-wave transmission possible.

The ionospheric layers are extremely variable with time and space and are extremely sensitive to the mood of the sun. The waxing and waning of solar activity during the eleven-year solar cycle is accompanied by changes in the reflectivity and other characteristics of the ionospheric layers. These changes may cause absorption of signals or propagation in unexpected directions or to unusual distances. They can be studied by analysis of a large number of radio contacts between distant points.

Propagation of radio waves occurs in a variety of ways, or "modes". The following paragraph describes briefly the modes under study in the IGY Propagation Research Program:

Radio waves travelling obliquely through the atmosphere may be scattered from inequalities in the ionosphere (*ionospheric scattering*); this provides transmission to distant points at frequencies for which the ordinary ionospheric reflection mechanism would not function. During sunspot maxima, ionospheric scatter is more extensive under the special ionospheric conditions which then prevail along paths crossing the equator (*transequatorial scatter*). Oblique incidence transmission may also be supported by reflection from clouds or patches of ionization in the E region (*sporadic E*), or by scattering from the long, thin ionization trails produced by meteors (*meteor scatter*). Another form of propagation arises by reflection from irregularities produced during auroras (*auroral reflection*). *Ground backscattering* occurs when a signal reflected from the ionosphere is scattered backward from the earth along the original path. Observation of all these modes of propagation yields information about the state of the ionosphere.

Outline of Program

During the IGY, the radio amateurs of the world are cooperating in recording data on v.h.f. (very high frequency) contacts by all modes of propagation affected by variations in the ionosphere. The US program is directed by the American Radio Relay League, Inc. (ARRL), under sponsorship of the US Air Force's Cambridge Research Center and the National Science Foundation. Large amounts of data are being gathered for the 50–54 and 144–148 megacycle amateur assignments, along with some information on 70, 220, and 420 mc.

Over 550 amateurs, or radio "hams," representing nearly 50 countries are taking an active part in the program, which is called the ARRL-IGY Propagation Research Project (PRP). They submit semi-monthly reports of the stations they contact or hear by means of the propagation modes described above. Nil reports are filed for intervals when the station is operative but nothing of interest is observed. A few of these stations maintain continuous, or "beacon," transmissions, and thereby give their fellow hams something definite to listen for.

Most amateur stations cannot supply precise quantitative data regarding signal strengths, azimuths, etc. They more than make up for this, however, by their extremely widespread distribution and by their enthusiastic approach, which has permitted amateurs to make the first use of virtually all known types of long-distance propagation. Through their efforts it should be possible to achieve an overall picture of worldwide propagation during the IGY that would be difficult to duplicate by any other means.

Reporting and Recording of Data

The report forms supplied to PRP observers call for: the date and the starting and ending times of the communication; the call sign and location of the other station; a rough idea of the signal's strength and fading rate and the direction from which it comes; the type of propagation the observer feels is responsible; and any pertinent comments. Such reports have been collected continuously since January 1, 1957, and will be collected through the end of the IGY. The six-months-early start served not only as a practice period, but also made it possible for much additional data to be collected as the sunspot cycle approached maximum.

As soon as all or nearly all of the reports for a given period have arrived at the PRP office, each entry on each form is carefully screened and evaluated according to propagation type and type of report. All items surviving this inspection are then transcribed onto special sheets in a partially coded form. Next, the latitude and longitude coordinates of each station (the observer's and the station he contacts or hears) are added to the sheets. To have this information available it has been necessary to maintain an up-to-date file concerning the locations of virtually all the several thousand amateur v.h.f. stations in the world.

At this point, the sheets go to an operator who prepares a punch card for each two-way contact report, heard report, negative report, and beacon report. A punch card presentation was chosen for the PRP data because it lends itself so well to high-speed automatic handling of the large quantities of information being gathered. During the twelve months of 1957, an average of more than 9600 cards per month were required to document the report items. The number will probably be somewhat higher in 1958; card punching and verifying for May has just recently begun. Peak reporting occurs during the early summer months, when sporadic-E propagation on 50 mc is at a high.

Once punched and verified, the cards for each month are put into chronological order and sorted out according to type of propagation. Cards reporting two-way contacts are examined for duplications—that is, two cards may be submitted for one contact when both stations are PRP observers. One card from each such duplicate pair is removed from the file and the other is punched to show it is a "confirmed" report.

At the present time, cards listing negative and beacon reports are being kept on file at the PRP office, while those citing positive results go to the Air Force Cambridge Research Center for further processing. This consists of preparation of a duplicate deck of cards plus the machine-computation of path lengths and midpoint coordinates for the single-hop sporadic-E reports and ionospheric forward-scatter reports. Listings of the single-hop sporadic-E reports are now being transmitted to the IGY World Data Center as soon as computations for each period are complete.

Another machine program has been evolved for determining the reflection point for auroral propagation, using the locations and antenna headings of the reporting stations. Due to the relatively small number of cases in which heading information is available from both ends of the path, however, this program has not yet been used.

Other Aspects of Program

Other work being done includes the publication of a monthly bulletin, *The PRP News*, which is circulated among the observers. This provides a brief summary of the preceding month's reports as well as other informational and instructional material of interest to radio amateurs. There is also an award system in which observers earn a certificate plus endorsement stamps for consistent reporting.

Further Uses of Data

There are a great many possible uses for this program's data after the IGY. The documentation of auroral and sporadic-E conditions has been particularly complete and should be of great value in investigations of these phenomena. In the case of transequatorial-scatter propagation, PRP reports have even more potential worth. Not only has much information been gathered for the Central and South American paths first noted by amateurs during the last sunspot maximum, but similar work has been done for the first time between Japan and Australia and between southern Europe and the Rhodesias. These additional circuits should help provide an insight into the seeming location selectivity of transequatorial propagation.

IGY stations operating in Chile and Peru under the direction of the National Bureau of Standard's Central Radio Propagation Laboratory have been of special help. These have been monitored by the amateur observers, and have been received in the United States and southern Canada with surprising consistency and with surprisingly variable fading and strength characteristics during the equinoctial periods.

Although punch cards have not been prepared for the F2-skip reports, they, together with the backscatter data, should furnish the actual highest usable frequencies over many varying paths for comparison with the predicted values and with those observed by other means.

The work of the hams has proved its worth many times in the past. It is expected that the ARRL-IGY Propagation Research Project will help fill a gap by making a large volume of amateur reports available to investigators in an easily usable form.

Weather at US-IGY Antarctic Stations During 1957

The following material was supplied by Edwin C. Flowers, meteorologist, US Weather Bureau.

The year 1957 was the first complete year of operation for most of the United States IGY stations in Antarctica. It was also the first year in history during which enough meteorological stations were in operation to give a synoptic picture of Antarctic weather.

Although it is much too early to answer the fundamental meteorological questions posed by the Antarctic environment, the observations made at US stations recorded facts about Antarctic surface and upper-air weather that had never before been documented. Highlights of the weather observations at each of the stations are given below.

IGY Little America Station

At IGY Little America Station, the year 1957 was warmer than any of the five previous years for which records are available (Table 1).

The extreme cold temperature recorded during 1957 (−53°C) was also considerably warmer than the absolute minimum over the period of record (−61°C), observed in 1956.

The past year was one of striking weather changes. Storms in June (a mid-winter month) gave that month an unusually warm average temperature. Thus, the June average of −23.9°C made it the warmest month since February. It was 7° warmer than May and nearly 12° warmer than July (see Fig. 1). The most sustained storm in June lasted, nearly without interruption, from the 13th through the 21st. On the 14th, the average wind speed for the day was 42 mph, with an average temperature of −8°C. The peak gust was 59 mph. As in nearly every case of strong winds at Little America Station the wind direction was from the NNE. During the stormy period, the temperatures rose rapidly with the increase in wind speed. Prior to the commencement of the storm, the minimum temperature was −46°C, while during the period June 13–21, the maximum temperature was −4°C and the minimum was −23°C. On the day following the cessation of the extreme winds, the temperature dipped to a minimum of −32°C.

This pattern of warming temperatures with strong winds is a normal feature in the Antarctic due primarily to mixing of the air in the inversion layer. The inversion layer consists of a stratum of air, from the surface to perhaps 500 m to 1000 m above the surface, throughout which the temperature rises with increasing altitude. At Little America Station in winter, the top of the inversion may be as much as 10–25°C warmer than the air next to the surface. An increase in wind speed in this layer causes turbulent mixing and a subsequent warming of the near-surface air.

Table 1. *Little America (and Framheim,* 1911): Average Annual Temperatures (°C)*

1911	1929	1934	1940	1956	1957
−27.2	−26.4	−25.7	−26.2	−25.1	−24.2

* Amundsen's camp. Near the present location of Little America Station.

The absolute minimum temperature for the year (−53.0°C) was recorded on May 24. The month of May also produced the warmest temperature ever recorded for that month (−1.0°C on the 11th). This was the greatest temperature spread for any month in 1957.

The average wind speed for the period April-September was 15 mph, while for the remaining six months the average was 12.5 mph. The sea-level pressure ranged from a high of 1030 mb on June 10 to a low of 931 mb on August 29. From January 30 through December 31, a total of 644 rawinsonde flights were made. The average height during the months April-September was 18.8 km; for the remaining months it was 21.3 km.

IGY Byrd Station

Nearly continuous storminess was the significant feature of the weather at Byrd Station during July, August, and September, 1957. These three months had average wind speeds of 22, 27, and 26 mph respectively. During August, ten days had daily average speeds greater than 30 mph and six days had average speeds greater than 40 mph, while only two days had average speeds less than 15 mph. Nearly all of the strong winds came from a northerly direction, usually with an easterly component. During most of the periods of storminess, the northerly winds were consistent throughout the troposphere above Byrd Station. They usually reached near jet velocities between 8 and 10 km above sea level. With strong winds, blowing snow becomes a hazard. During

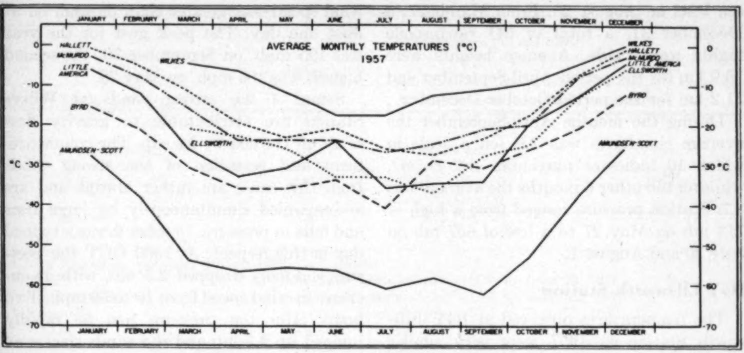

Fig. 1. *Average Monthly Temperatures for US-IGY Antarctic Stations and the Air Facility at McMurdo Sound During 1957.*

August, visibility was reduced to a quarter of a mile or less for this reason on four out of five days.

Despite the high incidence of strong winds, the station maintained an excellent record of rawinsonde flights. From March 23 through December 31, a total of 510 rawinsonde flights were made. Average heights were 16.4 km for the period April-September and 22.7 km for the period October-December. As at other high latitude Antarctic stations, minimum stratospheric temperatures in the range of −80°C to −90°C were a feature of the upper atmosphere during the three winter months. The yearly range of station pressures for 1957 was from a high of 833 mb on May 13 to a low of 775 mb on July 30 and December 9.

IGY Amundsen-Scott Station

Quite different weather prevailed at the Pole Station, where only one significant storm was observed. This occurred May 25–29, with wind speeds in the range of 25–50 mph. With the onset of this storm, the temperature rose from −69°C, with a 14-mph wind, at 0900 GCT to −46°C, with a 40-mph wind, 24 hours later. Only a few gusts greater than 40 mph were observed during the remainder of the year. However, winds of moderate speed prevailed nearly constantly throughout the winter months, producing for the period April-September an average speed of 18 mph. During June, of the 720 hourly wind speeds measured, 95% were in the range of 13–29 mph; of the remaining 5% of the hourly records, 4% were in the range 7–12 mph and 1% greater than 30 mph. No hourly winds of less than 7 mph were recorded during the month. The peak gust for the year was 54 mph, measured on May 25.

Throughout the winter, the surface inversion averaged 25°–30°C, with the top in the vicinity of 500 m above the surface. An extreme inversion of 41°C within 700 m occurred at 0600 GCT on September 18.

With the return of the sun, rawinsonde observations began to give indications of a rapid warming in the stratosphere. At 25 km, temperatures rose from −67°C to −24°C from the 1st to the 30th of October. This warming gradually became apparent in the troposphere, so that by mid-December miniumum temperatures measured in the upper air were in the range −45° to −50°C. The lowest temperature measured in the stratosphere was −91.2°C at 17.7 km above sea level on August 20. From March 27 to December 31, a total of 541 rawinsonde flights were made. Average heights were 16.9 km for the period April-September and 21.2 km for the period October-December.

During the months April-September the average cloudiness was 2.6 (on a scale in which 10 indicates maximum sky cover), while for the other 6 months the average was 4.7. Station pressure ranged from a high of 713 mb on May 27 to a low of 657 mb on July 30 and August 1.

IGY Ellsworth Station

The temperatures observed at IGY Ellsworth Station in 1957 were very similar to those observed at Little America Station as far as averages and extremes are concerned. The absolute minimum temperature for 1957 (−53.3°C) occurred on May 10. It is of interest to note that the synoptic weather situation that produced the Ellsworth Station minimum was at the same time bringing record cold (−73.6°C) to the Amundsen-Scott Station and record warm temperatures to Little America Station (−1°C) and to Byrd Station (−6.9°C).

The average wind speed for the months April-September was 14 mph; the prevailing wind direction was south for 5 of the 6 months. For the remaining 6 months, the average speed was 10 mph, also prevailing from the south. The peak gust for the year of 63 mph occurred on May 24. High and low station pressures for the year were 1014 mb on August 10, and 957 mb, on July 22. Between April 1 and December 31, a total of 496 rawinsonde flights were made.

IGY Wilkes Station

Wilkes Station experienced the warmest climate of the seven United States stations and, although not the windiest as far as averages go, it had the highest incidence rate for gale-force winds. In the month of August, wind speeds exceeded 58 mph on 13 days, although the average speed for the month was only 15 mph. During each of the 10 months of record for 1957, the wind speed was greater than 55 mph on at least one day. The peak gust for the year was 105 mph, on September 30; the second highest was 100 mph, on May 28.

Some of the strong winds at Wilkes Station are attributable to gravity flow of air off the nearby ice cap. The commencement and cessation of the strong winds from this cause are rather abrupt and are accompanied simultaneously by large rises and falls in pressure. October 9 was a typical day in this respect. At 1500 GCT the pressure suddenly dropped 2.5 mb, with an increase in wind speed from 10 to 50 mph. Two hours later the pressure just as rapidly jumped up 3.5 mb and the winds slackened to 10 mph. Although the prevailing winds are ESE (off the ice cap), the gravity flow only occasionally reaches these extreme speeds. Apparently, the location and height of the surface inversion with respect to the station is an important factor in the incidence of these strong winds.

During the month of December, rawinsonde flights at Wilkes Station were as follows: Of the total of 61 flights made during the month, 60 reached or exceeded the 50-mb pressure level (20.6 km above sea level); moreover, 56 of these reached or exceeded the 25-mb pressure level (25.6 km above sea level). The average termination height for this month was 26,992 m.

The minimum temperature for the year (−33°C) was recorded on July 24. For each month, with the exception of July and September, the maximum temperature reached 0°C or higher. The sea-level pressure ranged from a high of 1019 mb, on May 23, to a low of 951 mb, on September 10.

An ice-cap station, some 50 mi ESE of the main camp and at an elevation of about 1310 m, provided additional meteorological data for this region. At the ice-cap station, temperatures averaged about 10°C lower than those at the main camp. The minimum temperature of −48.2°C was measured on June 14. The average wind speed was about 25 mph, with a prevailing wind direction of ESE.

Table 2. *Averages and Extremes of Temperatures at US-IGY Antarctic Stations in 1957*

Station	Temperatures (°C) and Dates		
	Average	Max.	Min.
Little America	−24.2	+4.4 Jan. 3	−53.0 May 24
Byrd*	−27.6	−4.4 Nov. 29 Dec. 26	−56.9 June 11
Amundsen-Scott*	−48.7	−18.9 Dec. 15	−74.5 Sept. 17
Ellsworth*	−22.3	+1.8 Nov. 25	−53.3 May 10
Wilkes*	−8.1	+6 Dec. 20 Dec. 21	−33 July 24
Hallett*	−15.1	+4.0 Dec. 13	−42.0 Aug. 3
NAF McMurdo*	−16.7	+3.4 Dec. 23	−41.1 Aug. 2

* New extremes recorded during 1958, as follows:

Byrd	minimum temperature −59.7 on June 16, 1958
Amundsen-Scott	maximum temperature −14.7 on Jan. 12, 1958
Ellsworth	minimum temperature −55.6 on May 13, 1958
Wilkes	maximum temperature +8 in Jan. 1958
Hallett	maximum temperature +5.7 on Jan. 15, 1958
McMurdo	maximum temperature +4.4 on Feb. 4, 1958

IGY Hallett Station

Low-pressure systems moving past the station on their way into the Ross Sea area provided the Hallett Station with its most interesting weather. The annual temperature regime, with respect to monthly averages, was very similar to that observed at many other Antarctic stations, with a rapid drop in April and May, followed by warming in June, and another minimum in July and August.

The average wind speed for the months April-September was 9 mph; for the other 6 months the average was 10 mph. Prevailing direction was SW for 7 months and SSW for the other 5 months. The maximum gust measured was 114 mph, on October 23; two other months had days with wind speeds in excess of 85 mph. The storm of mid-October, which produced the 114 mph gust, interrupted a continuous series of 246 rawinsonde flights begun on June 23. The sea-level pressure ranged from a high of 1027 mb, on May 28, to a low of 955 mb, on July 23.

NAF McMurdo

The Naval Air Facility, at the foot of Observation Hill on Ross Island, McMurdo Sound, had its share of blizzard weather. During each month from May through November, maximum wind speeds of 65 mph or greater were recorded on at least one day. May had a peak gust of 96 mph, while a peak of 97 mph was measured in June. The average temperature for the months April-September was −23.9°C; the other 6 months had an average of −9.4°C. The sea-level pressure ranged from an absolute high for 1957 of 1041 mb, in May, to a low of 949 mb, in August.

During the period April-December 1957, 68% of the scheduled rawinsonde observations reached or exceeded the 50-mb pressure level and 19% reached or exceeded the 25-mb level. During September 1957, 51 observations (or 85%) reached or exceeded the 50-mb pressure level; 21 observations (or 35%) reached or exceeded the 25-mb level.

Table 2 lists the annual average temperatures and extremes during 1957 for the seven US-IGY stations (including the joint New Zealand-US Hallett Station). For the Wilkes and Ellsworth Stations, the period used to compute the annual average was March 1957 through February 1958. Figure 1 is a plot of the average monthly temperatures (°C) for the same seven stations.

Fourth US-IGY Satellite

The fourth US-IGY scientific earth satellite, 1958 Epsilon, was launched in a northeasterly direction from Cape Canaveral, Florida, a few seconds after 11:00 am EDT July 26, 1958. A little more than six minutes later the satellite, also known as Explorer IV, entered into an orbit which will cover an area between 51°N and 51°S latitude (see Fig. 2), as compared with approximately 34° for 1958 Alpha and Gamma. The launching vehicle was identical to those used for 1958 Alpha and Gamma except for an increase in thrust in the high-speed upper stages; the vehicle was developed jointly by the US Army Ballistic Missile Agency and the California Institute of Technology's Jet Propulsion Laboratory.

Satellite Characteristics: The steel satellite is 80 inches long, 6 inches in diameter, and weighs 38.43 lbs, about 7½ lbs heavier than its predecessors. Like 1958 Gamma, it does *not* carry a turnstile antenna with its four whip-like extensions; 1958 Epsilon's two dipole antennas utilize the skin of the satellite itself.

Instrumentation: 1958 Epsilon carries two Geiger-Mueller counters and two scintillation counters designed to measure corpuscular radiation at several levels of intensity. 1958 Epsilon's total concentration on corpuscular radiation studies was prompted by data obtained from the earlier Explorer satellites. This had suggested the existence of radiation of a very high intensity at altitudes greater than about 1000 km (about 600 mi).

The instrumentation on 1958 Epsilon was designed and developed by Carl E. McIlwain and George H. Ludwig of the State University of Iowa, under the direction of James A. Van Allen, head of SUI's Physics Department. The four detectors were developed by McIlwain, and are linked to an electronic system of measuring, scaling, and amplifying devices; the overall scientific package was engineered by Ludwig.

One of the Geiger-Mueller counters, shielded with 1/16 of an inch of lead, measures absorption of X-radiation and counts intensities of the more penetrating cosmic

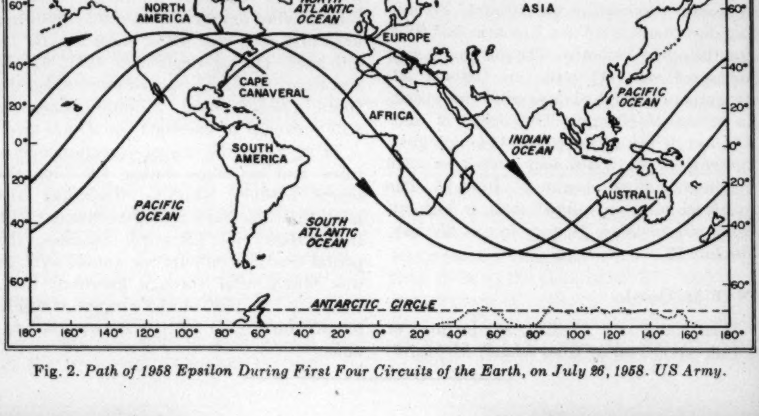
180° 160° 140° 120° 100° 80° 60° 40° 20° 0° 20° 40° 60° 80° 100° 120° 140° 160° 180°
ARCTIC CIRCLE
60° 40° 20° 0° 20° 40° 60°
NORTH AMERICA
NORTH ATLANTIC OCEAN
EUROPE
ASIA
CAPE CANAVERAL
AFRICA
PACIFIC OCEAN
INDIAN OCEAN
SOUTH AMERICA
AUSTRALIA
PACIFIC OCEAN
SOUTH ATLANTIC OCEAN
ANTARCTIC CIRCLE

Fig. 2. *Path of 1958 Epsilon During First Four Circuits of the Earth, on July 26, 1958. US Army.*

rays. The other counter has been scaled to handle some 1500 times the radiation intensity that caused the detection and scaling systems of 1958 Alpha and Gamma to blank out (see *Bulletin No. 13, July 1958*).

Scintillation counters use crystals of selected materials mounted directly on the faces of sensitive photoelectric cells, usually of photomultiplier type. The scintillators emit flashes of light when radiation passes through them. The resulting light pulses are converted into electric pulses by the photomultiplier.

One scintillation detector in Explorer IV makes use of a lightly-aluminized crystal of cesium-iodide as a scintillator. The integrated electric current from its photomultiplier provides an approximate measure of the total energy of the incident corpuscular radiation. A second scintillation detector utilizes an aluminized plastic scintillator and acts as a counter of incident corpuscular radiation.

1958 Epsilon carries two radio transmitters. The low-power transmitter operates on 108.00 megacycles at 10 milliwatts, the high-power transmitter on 108.03 mc at 30 mw. The battery life for each is expected to be about two months. Both transmitters broadcast the same five channels of telemetered information continuously, although the low-power transmitter is primarily for tracking purposes.

Tracking: Besides the Naval Research Laboratory's usual Minitrack network (see *Bulletin No. 2*), ten Microlock stations are tracking the satellite and recording its telemetered data. The stations are located at Cape Canaveral, Florida (JPL); Fort Monmouth, N. J. (Army Signal Corps); Van Buren, Maine (Army Signal Corps); Aberdeen Proving Ground, Md. (Ballistic Research Laboratories); White Sands, N. M. (BRL and JPL); Cedar Rapids, Iowa (Collins Radio Company); Temple City, Cal. (San Gabriel Valley Radio Club); China Lake, Cal. (Naval Ordnance Test Station); and Goldstone Test Station, Camp Irwin, Cal. (JPL).

The first precision photograph of the satellite was secured by the Baker-Nunn satellite tracking camera at Arequipa, Peru, at 12:53 am Universal Time, July 28, 1958. More than 230 Moonwatch teams were also in action. The first visual sightings of 1958 Epsilon by a Moonwatch team took place in Pretoria, Union of South Africa, at 3:20 am UT, July 29, 1958. The satellite was sighted by Roy Smith, who heads the Pretoria team.

Orbit: The Naval Research Laboratory reported the orbit of 1958 Epsilon, as of July 29, 1958, as: Period, 110.224 minutes; inclination of orbit to the equator, 50.13°; perigee, 157.3 statute mi; apogee, 1379.8 statute mi; velocity at perigee, 18,406 mph; and velocity at apogee, 14,232 mph.

Early Results

Preliminary results from about one-fourth of 1958 Epsilon's first 200 passes have been reported by State University of Iowa staff. They indicate that the intense radiation measured by 1958 Alpha and 1958 Gamma is not X-radiation originating within the satellite through bombardment of the satellite's skin by solar electrons, as believed at first. The data show, instead, that the Geiger-Mueller and scintillation counters in the satellite are being struck directly by high-energy charged particles, probably electrons. These may include hydrogen protons or other atomic fragments that have lost some of their electrons.

At least 60% of the charged particles readily penetrate the lead shielding one of the satellite's geiger tubes. The radiation intensity appears to double with each 60 mi above 250 mi., at least to Explorer IV's maximum altitude. According to SUI physicists, the satellite has found a radiation level of about 10 roentgens/hr at a height of 1200 mi above South America. This is more than 100 times the saturation level of the geiger tube in 1958 Gamma.

Cosmic Ray Program: First Twelve Months

This report is based on a summary of results in the IGY Cosmic Ray Program prepared by Scott E. Forbush, Department of Terrestrial Magnetism, Carnegie Institution of Washington.

Cosmic rays are extremely high-energy electrically-charged particles that continually bombard the earth from all directions. They attain their high energies—ranging from about 100 million to 10 billion billion electron volts (10^8 to 10^{19} ev)—within our galaxy. On rare occasions, our sun also produces charged particles with cosmic ray energies that reach the earth.

The primary cosmic rays reaching the earth's atmosphere consist almost entirely of protons (approximately 90%) and heavier nuclei. Their interaction with atmospheric particles creates "showers" of secondary particles. These include secondary protons and nucleons, pi mesons (charged and neutral), and heavier mesons.

Neutral pi mesons disintegrate into two gamma rays; these are ultimately transformed into electrons and photons and contribute to the soft (low-energy) component of cosmic rays. At surface level, this contribution to the low-energy component is small.

Charged pi mesons commonly disintegrate, forming charged mu mesons. The charged pi mesons that do not have time to decay before interaction with the atmosphere may cause new electron-nuclear showers, or nuclear fission disintegrations of the star type observed in emulsions.

Charged mu mesons constitute the high-energy, or hard, component of cosmic rays. Changes in intensity of the charged mu mesons are measured by heavily shielded ionization chambers and by heavily shielded counters.

Neutron monitors, on the other hand, are more sensitive to variations arising from changes in the intensity of the much lower energy primaries. For example, they indicate a latitude variation ten or more times greater than measured by shielded ionization chambers. In a neutron monitor, the cascade of atmospheric nucleons generates neutrons locally in the lead of a lead-paraffin pile. The paraffin slows down these neutrons to thermal energies; this increases the probability that they will be captured by the Boron-10 nuclei in the $B^{10}F_3$ gas used in the counter. After capture, the Boron-10 disintegrates into a lithium nucleus and an alpha particle. The 2.5 mev energy of these particles produces a pulse of ionization to trigger the counting circuit.

The fact that the IGY was scheduled for a period of maximum solar activity is of particular benefit to cosmic ray research. A number of significant advances have already been made in our understanding of cosmic rays and their causes, effects, and interrelationships with other phenomena. The following is a summary of some advances in cosmic ray knowledge by US investigators through the first 12 months of IGY.

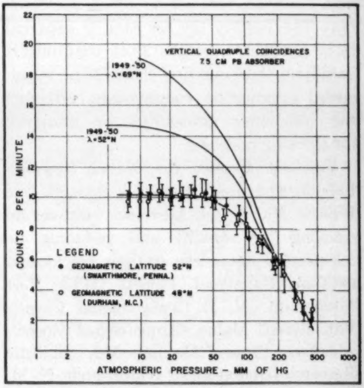

Fig. 3. *Variation of Cosmic Ray Counting Rates With Height at Geomagnetic Latitudes 52°N and 48°N. Data for geomagnetic latitude 52°N were gathered on three separate balloon flights; data for 48°N were gathered on four flights.*

Variations with the Solar Cycle

IGY scientists, using a variety of techniques, find that the beam of cosmic ray particles coming principally from the galaxy and arriving at the earth has drastically changed between the last minimum of solar activity (1954) and the present solar maximum (1957–58).

Mu-Meson Intensity: S. E. Forbush of the Department of Terrestrial Magnetism, Carnegie Institution of Washington, is supervising a long-term experiment involving continuous registration in ionization chambers of the mu-meson component of cosmic radiation. This work has continued over a period of two solar cycles and the records represent the longest continuous chain of cosmic ray data published. The results show an 11-year cycle of intensity variations roughly opposite in phase to that of sunspot numbers, but lagging about one year behind the sunspot numbers. Since the IGY is near a peak in the solar activity cycle, cosmic ray intensity is now relatively low.

The range of this variation in terms of monthly means is about 6%, as measured at Cheltenham, England; Huancayo, Peru; Christchurch, New Zealand; and Godhavn, Greenland. The variability of daily means from monthly means for 1957 was considerably greater than during the two previous sunspot maxima. Study of these variations in the mu-meson component of cosmic rays provides information on changes in the flux of relatively high-energy primaries.

Neutron Intensity: The solar-cycle variation is also exemplified by measurements made between 1954–55 and the first part of 1958 by J. A. Simpson and his colleagues of the University of Chicago. They found a decrease of 25% in neutron intensity at Climax, Colorado. They also showed that the ratio of neutron intensity at Climax to that at Huancayo decreased from about 1.25 in 1954 to about 1.08 in 1958, thus demonstrating a strong energy dependence on the 11-year intensity variation. Latitude surveys with neutron equipment in aircraft showed the proton integral-energy spectrum to be about E^{-2} in 1948 and in 1958, and about $E^{-2.7}$ in 1954. (The observed flux of particles arriving is proportional to the particle kinetic energy, E, raised to the indicated power.) On the basis of balloon flights between 1953 and 1958 it was shown that the 25% decrease in neutron intensity at Climax represents more than a twofold decrease between 1954 and 1958 for particles with energies of 1 bev or greater.

Ionization: IGY balloon flights carrying ionization chambers were made in 1957 at Thule under the direction of H. V. Neher, of the California Institute of Technology (see *Bulletin No. 11*). It was found that the ionization at an atmospheric pressure level of 15 gm/cm² (93,500 ft) was only half that in 1954, and that the number of primary particles had diminished by a factor of four. Similar observations at Thule in 1955 and 1956 showed that the intensity decrease followed closely an increase in sunspot numbers.

Vertical Particle Flux: A series of balloon soundings were made by J. R. Winckler and L. Peterson of the University of Minnesota in August-September 1955 at geomagnetic latitude 51.2°N to 64.2°N, and IGY flights were conducted at geomagnetic latitudes near 51.2°, 55.3°, and 58.6°N in June 1957, immediately prior to the beginning of the IGY. It was found that near the sunspot maximum in 1957–58 the vertical particle flux had decreased at all atmospheric levels greater than 300 gm/cm² (33,000 ft). It was also found that the magnitude of this decrease became greater with increasing height until, at high altitude and high latitude, it reached nearly a factor of two. These experiments showed that of the additional particles admitted at 10 gm/cm² (102,000 ft) in 1955 between geomagnetic latitudes 51.2°N and 58.6°N, at most only one-sixth remained in 1957, and that the relative latitude effect in this range was reduced from 40% to 10% or less.

Latitude Knee: With simultaneous balloon flights at geomagnetic latitudes 48°N and

52°N, near May 1, 1958, M. A. Pomerantz of the Bartol Research Foundation showed the variation with atmospheric height of the vertical quadruple-coincidence counting rate to be the same at both latitudes (see Fig. 3). (A quadruple-coincidence instrument is one that records the passage of those cosmic ray particles which trigger four separate, successive counters, thus indicating the angle of entry of the particle.) This indicated that the "knee" of the latitude effect—the latitude at which cosmic ray intensity ceases to increase with increasing latitude, represented graphically by a bend, or "knee," in the curve—was then south of 48°N. Similar observations in 1949–1950 showed no evidence of a true primary knee south of geomagnetic latitude 60°N.

Nucleonic Component: John A. Lockwood, of the University of New Hampshire, reports that from July 1954 to December 1957 the monthly mean intensity of the nucleonic component of cosmic radiation measured at Mt. Washington, New Hampshire—geographic latitude 44.2°N, elevation 6262 ft—decreased by 22%. The lowered intensity now prevailing came about through a series of sudden decreases. The largest of these occurred in February and November, 1956, and in January and September, 1957. After these decreases, the intensity recovered only partially. This long-term variation was accompanied by an increased number of day-to-day intensity changes.

Rapid Decreases During Magnetic Storms

During the past several years, it has become clear through the work of US investigators that the intensity of the cosmic radiation reaching the earth undergoes large changes with time, and that these changes are associated with electromagnetic phenomena on the sun. Phenomena that produce large changes in the cosmic ray intensity at the earth have become the central problem of interest. Not only does their study add to an understanding of cosmic ray and solar effects, but analysis of this data is leading to knowledge of magnetic fields in interplanetary space and to explanation of many magnetic storm effects at the earth's surface.

In 1957, large decreases in cosmic-ray intensity during magnetic storms were unusually numerous. Several US investigators have recorded large variations in daily mean neutron intensity for various intervals during the IGY. The sudden decrease in daily mean neutron intensity from August 29 to 30, 1957, was between 8% and 10% at IGY stations operated by the Universities of California and Chicago and the Bartol Research Foundation, Pennsylvania. This is about 2.5 times the change in ionization at Huancayo.

R. B. Brode, University of California, has reported daily means of neutron intensity at Berkeley and Hawaii for the period July 1, 1957–March 31, 1958. There is a good correlation between variations at these stations; variations are smaller at Hawaii, however, undoubtedly owing to the difference in geomagnetic latitude (see Fig. 4).

M. A. Pomerantz, Bartol Research Foundation, reports that values of daily means of neutron intensity at Thule (August 20, 1957–March 31, 1958) correlate well with values obtained by D. C. Rose at Ottawa and Resolute, Canada. Using balloons on several days between August 21 and September 18, 1957, Pomerantz also measured the vertical quadruple-coincidence rate under 7.5 cm Pb at altitudes above the 28 gm/cm^2 (80,000 ft) pressure level. These results show a decrease of about 20% near September 1 as compared with August 20.

Twelve-hour neutron-intensity means at Chicago from July 22 to September 1957 reported by Peter Meyer showed a range of nearly 20%. Meyer has also conducted balloon flights in Canada on days when the neutron intensity at Chicago differed, from one to another of these days, by 12%. His purpose was to determine whether the change in proton and alpha-particle flux is different at these two locations.

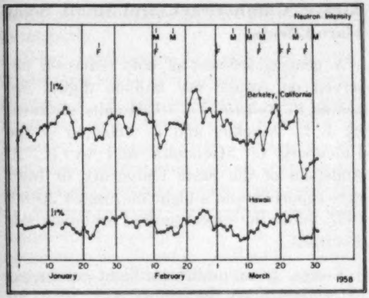

Fig. 4. *Comparison of Daily Means of Neutron Intensity at Berkeley, California, With Daily Means at Hawaii.* (*M = magnetic storm; F = solar flare*)

Flux of Alpha Particles and Heavy Particles

Investigation of the flux of the alpha-particle and heavy-particle components of cosmic rays is providing additional knowledge of the time scale of fluctuations of cosmic rays, their behavior at higher energy levels, and the variation of the heavier charge components of the primary particles with respect to solar activity.

Alpha-Particle Flux: P. S. Freier, E. P. Ney, and C. J. Waddington, of the University of Minnesota, report several determinations of the flux of primary cosmic ray alpha particles made during the past few years at high altitudes over Minnesota and over Texas. In an appreciable number of these determinations, small stacks of nuclear emulsions were carried aloft by balloons for use as detectors.

In such a flight made just prior to the IGY, Freier and Ney found that the flux over Minneapolis had fallen from its previous value of about 280 alpha particles/$m^2 \cdot$ster$\cdot$sec (the number of particles passing through a one-square-meter area each second from directions lying within a unit solid angle, or steradian) to a value a little more than half that. A flux value of 138 ± 9 alpha particles/$m^2 \cdot$ster$\cdot$sec was determined; another stack, exposed at the same place some 3½ months later, indicated that this decrease was not a transient effect.

The latter flight was made during a large Forbush decrease. While there does not appear to have been a significant difference between the total fluxes observed in the two stacks, there was a significant reduction of low-energy particles. In the first stack, the flux of alpha particles with energies below 700 mev/nucleon was 47 ± 8/$m^2 \cdot$ster$\cdot$sec (the old value was 120 ± 10), while in the second stack it had fallen to approximately one-half this value.

Yet another flight made about 1½ months later over Texas, where the cut-off energy is approximately 1.5 bev/nucleon, showed that the flux of these high-energy particles had declined by about one-third from the previously measured value of 97 ± 8/$m^2 \cdot$ster$\cdot$sec.

In each of these stacks, the energies of the low-energy alpha particles were determined from a measurement of their ionization, using a photodensitometer.

In addition to the ionization measurements, energy determinations were made from multiple-scattering measurements on about half the alpha particles observed in the second stack exposed over Minnesota. These suggest that the present integral-energy spectrum is not as steep as it was previously, and that the new flux obtained over Texas agrees closely with that predicted from the Minnesota measurements.

H. Yagoda has reported measurements of the time variation of the omnidirectional flux of heavy primaries, as obtained by small emulsion blocks exposed in rockets at geomagnetic latitude 41°N between December 1952 and October 1957. The experiments were carried out with the cooperation of GRD-AFCRC. They show a 10–20% diminution in intensity roughly coincident with a period of maximum sunspot activity, in 1957 (see Fig. 5). The small effect at low geomagnetic latitudes parallels more pronounced variations both in the total ionization and in the alpha-particle

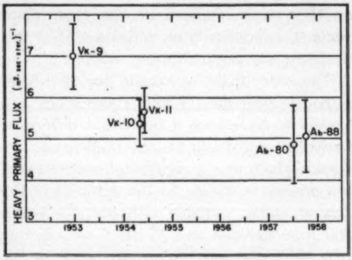

Fig. 5. *Decrease in Omnidirectional Flux of Heavy Primaries, 1952–58, at Geomagnetic Latitude 41°N. Vk numbers represent flights using Viking rockets; Ab numbers, Aerobee flights.*

flux at geomagnetic latitude 55°N during the same period, as indicated by exposure of emulsions near maximum balloon altitudes (about 100,000 ft). Yagoda suggests that the heavy primary component of the cosmic radiation follows time variations related to the solar cycle.

Proton and Alpha-Particle Time Variations: Using a simplified combined scintillation and Cerenkov counter on balloon flights over Prince Albert, Canada, the time variation of the protons and alpha particles was measured separately by Peter Meyer of the University of Chicago. A detailed analysis has been completed only for the flights on August 30 and September 16, 1957. While the neutron intensity at Climax was 12% greater on the latter date than on the former, the proton intensity over Prince Albert was 16% greater and the alpha-particle intensity 25% greater. Meyer feels that these results are consistent with a common modulating mechanism for protons and alpha particles. On both flights, the alpha-particle flux seemed to increase appreciably during the eight hours the equipment was at altitude without a corresponding change in proton intensity. These independent changes in alpha-particle and proton intensity cannot be accounted for by any modulation mechanism so far considered.

X-rays, Gamma-rays, and Small Solar Flare Effects

A general account of soft radiation observed on cosmic ray balloon flights appeared in *Bulletin No. 10*. Results obtained by J. L. Winckler and L. Peterson of the University of Minnesota and by K. A. Anderson of the State University of Iowa were reported, and a flight on August 29–30, 1957, under the supervision of Anderson was described.

X-rays: In an additional flight conducted by Anderson on September 1–2, 1957, an X-ray shower not associated with a magnetic storm, as in the August 29–30 event, was observed. The radiation was present even before the balloon reached ceiling altitude, at 1420 UT, and was still detectable 12 hours later. After some early time variations, the radiation slowly diminished in a roughly linear fashion. The ion-chamber to single-counter ratio changed very markedly (more than threefold) during the flight, particularly during the first hour after ceiling altitude was reached. The ratio became so high at times that there appeared to be no way to attribute the radiation to X-rays. During the greater part of the event the ratio was characteristic of 100-kev X-rays, although ratio evaluation becomes inaccurate as the X-ray intensity diminishes.

It was established on several night flights made while the regularly appearing auroral forms were present that these forms contributed a small quantity of soft radiation at the altitude of the balloon.

The University of Minnesota workers estimate that the current of high-energy electrons producing the X-rays in the Minneapolis experiments described in *Bulletin No. 10* is at least 3×10^6 electrons/cm^2/sec, and probably an order of magnitude greater. It is, therefore, approximately equal to auroral proton fluxes and to the fluxes observed in soft radiation at rocket heights. The X-ray bursts usually appear when a homogeneous auroral arc develops a strong ray structure, or when rays increase in intensity.

X-ray bursts were also observed during the auroral storm of February 10–11. These showed a strong correlation with large magnetic bays (increases or decreases in intensity of magnetic-field components, recorded as bay-like indentations in the graph of intensity variations with time) observed at Fredericksburg Observatory and with cosmic-noise absorption in the ionosphere observed at Boulder, Colorado. X-ray bombardment in the daytime was observed on several other occasions during sudden intensity decreases in cosmic radiation accompanied by increased geomagnetic activity. However, no auroral correlation was possible.

Solar Gamma Rays: During a balloon flight in Cuba, a strong burst of what are believed to be solar gamma rays was observed by the University of Minnesota investigators coincident with a solar flare. The burst lasted 18 seconds and was also exactly coincident with a strong radio-noise burst. The energy of the gamma radiation was estimated at 0.5 mev. The investigators believe it may have arisen from nuclear processes excited during the flare, since it is difficult to account for by more usual mechanisms.

Latitude Effect: The remarkable latitude effect reported in *Bulletin No. 3*, in which changes of cosmic ray intensity could be detected within a latitude change of as little as seven miles at Minneapolis in the fall of 1956, has now vanished owing to the removal of low-energy particles from the cosmic ray spectrum during the solar maximum in 1957–1958. At present, no change with latitude is detectable. A large effect is still detectable at Texas, as the

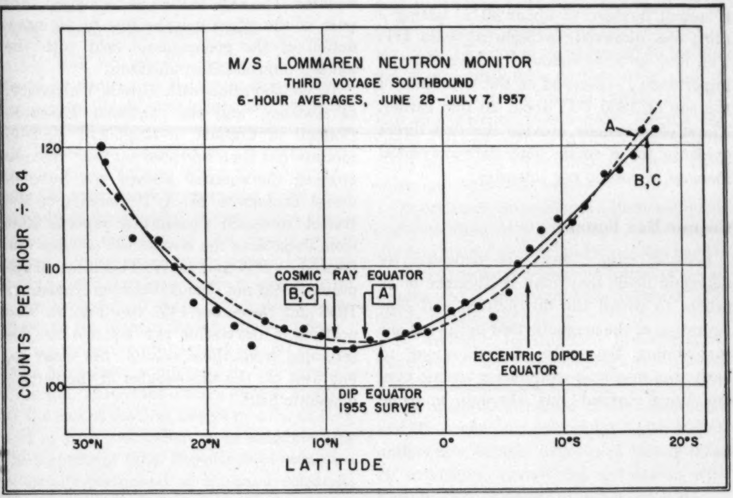

Fig. 6. *Typical Set of Data Used to Locate the Cosmic Ray Equator (line of minimum cosmic ray intensity). A, B, and C are analytical curves of successively higher order fitted to the data by the least-squares method to provide a smooth variation through the experimental points. (Although they represent second- and third-order mathematical terms, respectively, curves B and C are identical.)*

energies still present in the primary spectrum are latitude-sensitive at that location.

Rapid Fluctuations: The cosmic ray monitoring program in general shows many fluctuations of the primary radiation at 100,000 ft which are well correlated with fluctuations observed at sea level by neutron monitors and by ion chambers.

Balloon experiments were conducted by J. J. Corrigan, S. F. Singer, and M. J. Swetnick, of the University of Maryland, to detect rapid fluctuations in the low-energy component of cosmic rays and to detect small solar-flare effects. A high-counting-rate Geiger telescope was flown in an aircraft at altitudes of 25,000 to 45,000 ft at geomagnetic latitude 55°N.

No rapid fluctuations were observed on a flight on August 8, 1957, but at 1349 UT, August 9, while the balloon was flying at 25,000 ft, an increase of about 30% began. It lasted about 2.7 min. At the same altitude, a second increase of about 30%, lasting 2 min, was observed to begin at 1433 UT. The first increase followed a solar flare of importance 1, observed on the west limb of the sun at 1330 UT, about 20 min earlier. These observations provide the first direct evidence for a small, solar-flare-associated increase in cosmic ray intensity.

Cosmic Ray Equator

Because cosmic rays are deflected by magnetic fields they may be thought of as probes to reveal the distribution and configuration of the magnetic field in the regions surrounding the earth. Investigations to locate the magnetic equator for cosmic rays are being carried out through multiple crossings of the equatorial region by ships and aircraft.

Investigation of the location of the magnetic equator for cosmic ray particles, under the supervision of J. A. Simpson, University of Chicago, was begun with the USS *Atka* and by three round-the-world Antarctic expeditions of the USS *Arneb*. The ships carried cosmic ray neutron monitors back and forth across the equator. In addition, twelve equatorial crossings were carried out within a short time interval by high-flying aircraft fitted with neutron detectors.

As a result of these investigations, a 25% variation of maxima with longitude was determined for the first time. Also, results show that the magnetic center of the earth for cosmic ray particles is about 45° west of the magnetic center derived from spherical harmonic analysis of geomagnetic data. The cosmic ray equator was found to lie close to, but west of, the surface magnetic-field dip equator. The shift is such as to suggest that part of the effect may be due to an interaction of the geomagnetic field with the ionized interplanetary medium.

In collaboration with Upsala University, of Sweden, and the National Research Council of Canada, a shipboard neutron monitor has been operated on four voyages crossing the equator aboard the Swedish vessel *Lommaren*. M. A. Pomerantz of the Bartol Research Foundation reports that from these data the cosmic ray equator was located at 8°N and 14°W. This location apparently did not change between November 1956 and December 1957 (see Fig. 6). The position of the cosmic ray equator as determined from these results, lies close to, but west of, the dip equator of the earth's magnetic field.

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IGY BULLETIN

A monthly survey by the U. S. National Committee for the International Geophysical Year. Established by and part of the National Academy of Sciences, the Committee is responsible for the U. S. International Geophysical Year program in which several hundred American scientists are participating and many public and private institutions are cooperating.

Oceanography Program: First Twelve Months

The following report is based on material supplied by Gordon G. Lill, Head, Geophysics Branch, Office of Naval Research, Washington, D. C., Roger R. Revelle, Director, Scripps Institution of Oceanography, La Jolla, California, and other participants in the IGY Oceanography Program.

Deep Water Ship Operations

The IGY brought the element of international cooperation to the systematic study of the oceans. Single institutions and countries have lacked sufficient oceanographic vessels for large-scale, coordinated investigations. But in the IGY Deep Water Ship Program, over 20 countries are operating more than 80 ships in coordinated studies of the circulation and currents of the major ocean basins. Cruises vary from several hundred miles to 40,000 miles or more in length, from a few days for off-shore observations to as much as ten months for extended studies.

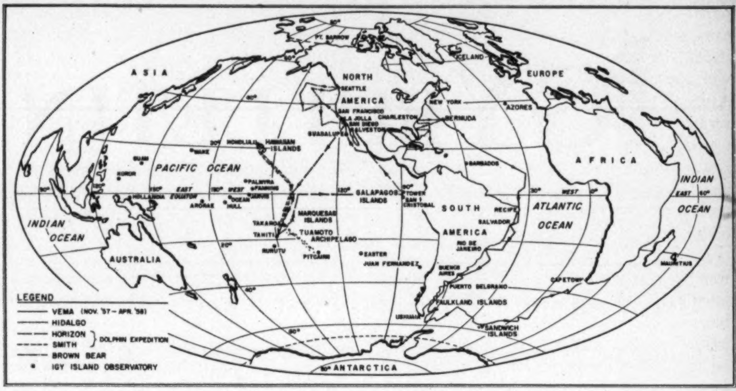
Five extensive cruises and several shorter ones have been completed in the US-IGY Program. Three long cruises were in progress at the end of the first twelve months of IGY and at least two others were scheduled for the summer of 1958. Because data reduction is usually performed by the same scientists who carry on the cruise work, results are not yet available from all cruises. However, a number of important findings have already been announced.

Vema: The oceanographic vessel *Vema*, of the Lamont Geological Observatory, Columbia University, made her first IGY cruise, from New York to Recife, Brazil, just prior to the beginning of IGY. The *Vema* then left Piermont, New York, on November 8, 1957 on an Atlantic Cruise to Capetown, South Africa, arriving there on April 7, 1958 (see Fig. 1). This was the first half of an extended cruise expected to end in September 1958. The cruise was planned to include the Scotia Sea, east of the lower end of South America, the Indian Ocean, and the Red and Mediterranean Seas. During the South Atlantic portion of the cruise, cooperative operations were conducted with Brazilian and Argentine vessels.

Objectives were to obtain a more complete understanding of the geologic structure of the continental shelves and the ocean basins, to study the large-scale circulation of ocean waters, and to investigate the nature of sediments on the ocean floor.

In addition to standard oceanographic instruments, the *Vema* is using a new nuclear precision magnetometer, new equipment for study of the CO_2 content of the atmosphere and the ocean on a continuing basis, and an underwater camera capable of taking some 70 exposures, permitting correlation with bottom data gathered by other methods.

To study the geologic structure beneath the ocean floor and the continental shelves, seismic refraction measurements are made by two ships working together. The Bra-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HAWAIIAN ISLANDS
WAKE
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KOROR
PACIFIC OCEAN
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MARQUESAS ISLANDS
TAKAROA
TAHITI
TUAMOTO ARCHIPELAGO
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EASTER
JUAN FERNANDEZ
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SALVADOR
RIO DE JANEIRO
BUENOS AIRES
PUERTO BELGRANO
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LEGEND
VEMA (NOV. '57 – APR. '58)
HIDALGO
HORIZON
SMITH
DOLPHIN EXPEDITION
BROWN BEAR
IGY ISLAND OBSERVATORY

Fig. 1. *Tracks of 1958 IGY Oceanographic Cruises, and Locations of IGY Island Observatories*

Table 1. Types and Number of *Vema* Observations

Program	*No. of Observations*
Standard hydrographic stations	43
Oxygen samples	956
Salinity samples	986
Reversing thermometer water temperature determinations	956
Carbon-14 samples	52
Tritium samples	57
Underwater camera stations	40
Sediment cores	72
Seismic refraction profiles	115
Reversed	15
End-on	100
Plankton hauls (horizontal)	70
Vertical biological hauls	75
Bottom biological trawls	38
Bathythermographic observations	1275
Sub-bottom depth recorder track (nautical miles)	900
Precision depth recorder track (nautical miles)	18,000
Magnetometer observations (nautical miles of track)	16,900
Carbon Dioxide measurements	
Nautical miles of continuous observations	18,000
Number of single samples run	150

zilian vessel *Forte de Quimbia* and the Argentine vessel *Sanaviron* cooperated with the *Vema* in the occupation of seismic stations along the continental shelf of South America and in adjacent waters. The geologic structure beneath bays and several estuaries was studied using a sub-bottom depth recorder, a new instrument similar to the echo sounder.

Table 1 provides a count of observations of different types made by the *Vema* on this first portion of the cruise.

Crawford: The research vessel *Crawford*, of the Woods Hole Oceanographic Institution, has added several Atlantic sections to its earlier work, completed in the pre-IGY period (see *Bulletin No. 2*). In addition, it conducted some significant studies in the Caribbean Sea.

The *Crawford's* observations will be compared and correlated with similar data obtained by the Woods Hole research vessel *Atlantis* 30 years ago in the hope that this will shed new light on the circulation of the Atlantic Ocean. Efforts will be made to determine the age of the water in the enclosed Caribbean Basin. Of particular importance is knowledge of the depths of sills—submarine ridges separating partially closed basins from one another, or from the adjacent ocean, and blocking exchange of deep water.

During the *Crawford's* cruise, some basins were found in which the deep water is isolated from both North Atlantic and Caribbean deep waters. Moreover, the characteristics of this isolated water suggest that it is residual from previous ocean circulation patterns that existed under different climatic conditions.

The water samples collected on the cruise, along 10 transverse Atlantic sections, provide for the first time adequate information about the distribution of organic and inorganic phosphorous in the sea. On the basis of this information, the Woods Hole scientists now believe that plankton productivity in the open sea may be twice previous estimates.

Hidalgo: The research vessel *Hidalgo*, of Texas Agricultural and Mechanical College, is now carrying out an IGY oceanographic cruise in the Atlantic, Caribbean, and Gulf of Mexico (Fig. 1). This cruise is intended to tie into Lamont and Woods Hole cruises to help fill gaps in our knowledge of the oceans to the south and southeast of the United States.

Atlantis: The *Atlantis*, of Woods Hole, left late in April of this year for the Indian Ocean, via the Mediterranean and Red Seas. She met the *Vema* of Lamont Geological Observatory in the Indian Ocean, where the two ships conducted seismic operations to study the sub-oceanic crust and made standard oceanographic observations. They then made traverses of the Red Sea, which had never before been studied in this manner. The floor of the Red Sea is thought to consist of a gigantic rift; in the Red Sea itself, deep water of very high salinity has been observed. In July, the ships worked in the Mediterranean Sea, returning to the United States in late summer through the Atlantic.

Brown Bear: In the summer of 1957, the University of Washington research vessel *Brown Bear*, made a cruise in the Northeast Pacific (see *Bulletin No. 9*). A unique feature of the University of Washington program was the conversion of data to punch cards while still aboard ship.

A second IGY cruise of the *Brown Bear* got under way on June 30, 1958. The region under study was the eastern Pacific between about 32° and 50°N, and as far west as about 146°W (Fig. 1). The cruise plan included reoccupation of stations occupied 30 years ago by the *Carnegie*, of the Carnegie Institution of Washington, for comparison of present-day data with that obtained by the *Carnegie*. The ship returned to Seattle, its home port, on August 24.

A special objective of the cruise was to determine the location of the transition zone between the subarctic and central regions of the northeastern Pacific. As on the 1957 cruise, data were transferred to punch cards aboard ship.

Downwind Expedition: The *Horizon* and *Baird*, research vessels of the Scripps Institution of Oceanography, University of California, completed a five-month expedition in the Southeast Pacific—the "Downwind Expedition"—in February 1958. *Bulletin No. 7, January 1958*, describes the aims of the expedition, techniques used, and results of the first few weeks' work. From this information and from data collected on the remainder of the expedition some preliminary conclusions are possible.

There are indications that North Pacific deep water extends to the Tuamotu ridge, a projection of the East Pacific rise. South of the Tuamotu ridge, the deep water is of Antarctic origin.

It was found that in regions of uplift of the earth's crust beneath the oceans, such as the Easter Island Rise (the Albatross Plateau), the heat flow in bottom materials was larger than normal. Near regions of severe downwarping of the crust, in the vicinity of the South American Trench along the western edge of the continent, for example, the values were much lower than expected. These findings support the theory that great convection currents exist within the earth's mantle—the layer directly beneath the crust. These currents are believed to carry hot material upward toward the base of the crust in regions of uplift and cooled material downward toward the core of the earth in regions of downwarp. Such convection currents may actually be the cause of the uplifts (plateaus) and downwarps (trenches).

There was considerable variation of crustal thickness beneath seismic stations occupied on the cruise. A basin just east of the Easter Island Rise had one of the thinnest crusts yet found—2 km, or less than half the normal sub-oceanic crustal thickness. Beneath Nasca Ridge, on the other hand, at an average depth of 1600 fathoms, one of the greatest sub-oceanic crustal thicknesses was discovered—perhaps as much as 15 km.

Preliminary analysis aboard ship of some of the seismic data gathered in the equatorial zone of carbonate bottom sediments confirmed previous observations that this sedimentary layer is about twice the mean oceanic sediment thickness of a few hundred meters. Bottom sediment thicknesses observed during the Southeast Pacific part of the cruise, on the other hand, were no greater than normal thicknesses in the Central and North Pacific. At nearly all stations occupied on the cruise, a "second layer" was found between the unconsolidated sediment and the principal crustal layer. Its thickness is generally about 1 km, although in some places it is several km thick.

Ionium/thorium ratios at various depths in the ocean-bottom sediments indicate that the rate of accumulation of these sediments can be measured in millimeters over thousands of years.

One unusual finding was the discovery of an extensive area in which the sea floor is covered with a loose layer of nodules having rich concentrations of manganese, copper, cobalt, and nickel.

Dolphin Expedition: In the spring of 1958, the research vessels *Horizon*, of Scripps, and *Hugh M. Smith*, of the Pacific Oceanic Fishery Investigations, US Fish and Wildlife Service, completed a two-months' cruise in the Equatorial Pacific (Fig. 1). The cruise, called the "Dolphin Expedition," explored the Cromwell Current which runs counter to the South Equatorial Current some hundreds of feet beneath it.

This eastward-flowing countercurrent, first discovered at 150°W in 1952, has now been traced for about 3500 mi. Although the origin and westward extent of this current are still unknown, the Dolphin Expedition has established that it disappears at the Galapagos Islands. The countercurrent is about 250 mi wide and has a speed of approximately 3.5 mph; this is more than 2 mph faster than the South Equatorial Current, which flows westward above it. Expedition members first located the countercurrent 100 ft beneath the surface. Its core lay about 300 ft below the surface, becoming shallower eastward, and its total thickness was found to be about 700 ft. This countercurrent transports a volume of water approximately equal to that moved by the Gulf Stream where it emerges from the Straits of Florida. It is thought that this great countercurrent may be an important refertilization mechanism, contributing to the unusual abundance of marine life in this part of the equatorial Pacific.

Beneath this swift, eastward-flowing countercurrent still another current—a weak one, flowing westward—was found. Thus, in the upper few thousand feet of this part of the Pacific there are three ribbon-like currents, lying one on top of another and flowing in opposite directions.

Antarctic: The logistic support afforded the IGY Antarctic Program by US Navy Task Force 43 presented an opportunity for limited oceanographic studies in Antarctic waters by scientists aboard Navy and Coast Guard icebreakers.

Detailed temperature profiles of the Antarctic Convergence have been largely lacking in the past. (The Antarctic Convergence is the zone in which the cold waters of the Antarctic Current sink beneath, and to some extent mix with, the warmer waters of the West Wind Drift.) Hence, special emphasis was placed on such work during the cruises and new information was gathered on the geographic location of the Convergence. In the Indian Ocean sector, the Antarctic Convergence was identified in the vicinity of 55°S. Crossings in the Atlantic sector located it near 56°S, 55°W and near 52°S, 38°W. In the vicinity of the International Date Line, in the Pacific sector, the Convergence was found near 62°S.

Because icebreakers are now able to penetrate deeply into ice-locked Antarctic regions, they have obtained oceanographic data in places hitherto inaccessible and at times during which scientific field study was formerly impossible. Stations in the Weddell Sea in 1956–57 indicate that there is very little change of density with depth. Across the head of the Sea, on the continental shelf, the water temperature was uniformly slightly above −2.0°C from a depth of 100 m to 600 m. Air temperatures ranged from −2.8°C to −6.2°C. Therefore, although it was less than a month past Antarctic midsummer (January 11–20), the sea was losing heat to the atmosphere, and winter cooling had already begun.

Weddell Sea studies verify the theory that Antarctic bottom water is formed by a mixing of the cold, heavy surface water—originating on the continental shelf by winter cooling and freezing—with the warmer circumpolar subsurface water.

In the Ross Sea, one of the highest densities ever met in the ocean—28.14 (gm/liter above 1 kg)—was obtained at a depth of 515 m, only 5 m above the bottom. This suggests the existence at that location of a basin in which very dense water is trapped.

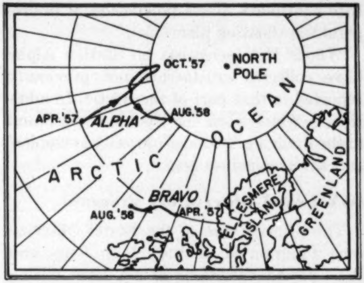

Fig. 2. *Tracks of IGY Drifting Stations Alpha and Bravo Since Their Occupation.*

Oceanographic stations were reoccupied periodically over several months' time near IGY Little America Station and near Hut Point, in McMurdo Sound. At both places there was a rapid summer decrease in salinity, apparently reflecting melting of the pack and shelf ice; warming of the sea was confined to the upper layers. During the winter, cold brines sinking from beneath the thickening pack ice raise the salinity of the waters over the continental shelf.

Marked differences between the regimes of the waters near Hut Point and near Little America Station are probably caused mainly by the difference in the thickness of the ice bodies near these waters. In the vicinity of Hut Point the ice barrier is relatively thin compared to the 250-m thickness of the Ross Ice Shelf near Little America.

Drifting Stations: In the Arctic Ocean, IGY oceanographers pursue their investigations from stations on the drifting pack ice (Fig. 2). This and other Arctic Basin work and some of the results obtained were reported in *Bulletins Nos. 1, 2, 4, 6, 8, 9,* and *12.*

Further results are continually being made available: Hydrographic observations made at Drifting Station Alpha show a uniform temperature of −1.7°C (+29.0°F) from the surface to a depth of 900 ft. Micrometeorological observations indicate that this value has remained constant for a considerable length of time. Regular plankton hauls indicate continued sparse population of phytoplankton (floating plant life).

Woods Hole scientists on Station Alpha have collected crustaceans not previously reported in that part of the Arctic. In addition, a water-worn coral pebble was found in the dredging. (Coral grows only in tropical and sub-tropical waters.)

IGY Island Observatory Program

The primary aim of the Island Observatory Program is to study both long- and short-period variations of sea level during the IGY. A number of other phases of oceanographic work are included. Sea-atmosphere relationships receive particular emphasis (see *Bulletins 2*, *4*, *6*, and *9*).

In the Pacific, the Island Observatory Program is directed by the Scripps Institution of Oceanography. The Atlantic program is directed by the Lamont Geological Observatory. Many other US agencies and individuals are contributing directly to the work, and Iceland, Chile, Ecuador, France, Great Britain, Portugal, and Mexico are cooperating in joint projects. United States agencies assisting in the program are the Coast and Geodetic Survey, Weather Bureau, Navy, and Fish and Wildlife Service.

Analysis of data gathered at Pacific observatories (Fig. 1) has yielded the following results, among others:

Long-Period Waves and Local Weather: Qualitative study of the daily background at the long-period wave stations indicates that local weather is directly related to the amplitude of sea swell and surfbeat. Short trains of long-period waves (10–90 min) occur daily. Marcus Island records show several occasions during which local squalls passing over or near the island produced sea-level changes that quantitatively corresponded to variations in barometric pressure.

Hurricane Waves: Four hurricanes occurred during the period November 1957–April 1958; the waves from each were recorded at one or more stations. The first wave arrivals consisted of long undulations of sea level with periods of 10–20 min. These were followed by great intensification of the surfbeat and the sea swell. The entire process from normal to peak activity occurred within three hours at stations within 200 mi of the disturbance. At distant stations, as much as 24 hours elapsed between the long-period forerunners and the swell.

Tsunamis: A statistical study of inundation heights from tsunamis (so-called tidal waves resulting from submarine earthquakes, landslides, or volcanic action) around the Hawaiian Islands is in progress. The study indicates that the local height of on-shore waves on a nearly circular island can be adequately represented by a simple empirical equation. Using this equation, an apparent inverse relationship was found between the individual wave heights and the offshore slope. In all cases, the distance from crest to crest at the beginning of the slope was of the order of magnitude of the island diameter.

Hemispheric Water Exchange: Tide-gauge data from both oceans show a change in mean sea level from summer to winter. Most of this appears to be related to expansion and contraction of water with seasonal temperature changes, but it may also be due to movement of water between northern and southern hemispheres.

Carbon-Dioxide and Radiochemistry Studies

Carbon Dioxide: A coordinated effort is being made by scientists at Scripps, Woods Hole, Lamont, the University of Washington, and Texas A & M to gain an understanding of the CO_2 content of the atmosphere and oceans.

Man, in his burning of fossil fuels and denudation of the land's surface, may be performing a gigantic geophysical experiment in which the CO_2 cycle is being influenced. It is thought we may be increasing the CO_2 input into the atmosphere by 70% in 40 years, although it is not certain how much of this may be absorbed by the oceans. A substantial increase in CO_2 content in the

Table 2. Radiochemical Analyses

Woods Hole	*Scripps*	*Lamont*	*Texas A & M*	*U of Wash.*
H^3, C^{14}, Sr^{90}, Sb^{125}, Cs^{137}, Ce^{144}, Pm^{147}	H^3, C^{14}, S^{89}, Sr^{90}	H^3, C^{14}	C^{14}	C^{14}

air would trap more of the earth's radiated heat and cause a warming of temperatures.

Data collected during the IGY will be needed for comparison with measurements made 15 to 25 years from now to determine whether the CO_2 content is changing. It is now possible, owing to availability of a gas analyzer capable of a precision of $\frac{1}{10}$ part per million (ppm), to achieve the accuracy required for such determinations.

Atmospheric CO_2 measurements made on the Downwind Expedition indicated a very slight but distinct latitudinal variation. Its range was about 3–4 ppm. In general, it was found that CO_2 tension in the sea water, that is, the part of the total pressure caused by CO_2, exceeded that in the atmosphere. An observation near the Chilean coast showed extraordinarily high CO_2 tension, apparently the result of upwelling of the deep water.

Results of IGY investigations thus far indicate a remarkable constancy of CO_2 content in the atmosphere. At IGY Little America Station, Antarctica, the variation during a period of more than one year was only 0.3%. Continuous measurements over a period of two months at Mauna Loa Observatory, Hawaii, showed a variation of 1.0%. Measurements made continuously aboard research vessels in the Pacific between the Bering Sea and Valparaiso, Chile, in 1957, show a variation of 2.0%. The mean values for all of these locations lie very close together. Air samples collected in the Gulf of Alaska and at Cape Hatteras in April 1958 also yielded concentrations of CO_2 whose mean values were very close to those obtained at the above locations.

Radiochemistry: Those institutions carrying out the CO_2 program are also performing radiochemical analyses of sea water. Such analyses are used to determine the circulation of the oceans and the age of sea water at various levels. Table 2 lists the kinds of radiochemical analyses being made at the participating institutions.

Future Plans

The international cooperation which is such an integral part of the IGY has had a profound impact on oceanographers. As a result, the International Council of Scientific Unions (ICSU) has organized a Special Committee on Oceanographic Research (SCOR) to foster similar cooperative programs in the future. Several meetings of SCOR have already been held, and plans have been made for a long program of oceanographic research in the Indian Ocean, about which little is now known. In the course of this work, encouragement and training will be given to scientific talent in bordering countries. Similar work will eventually be performed elsewhere.

The National Academy of Sciences has also recognized the need for long-range planning in oceanography, and has organized a new Committee on Oceanography, under the chairmanship of Harrison Brown, California Institute of Technology. The Academy's Committee contains several panels to study specific questions, such as design of oceanographic research vessels, new devices to explore the oceans, and marine resources. The Academy's Committee will carry out liaison with SCOR.

The planning of both SCOR and the Committee on Oceanography carries far beyond the specialized IGY program in oceanography. Included are marine biological studies, with emphasis on fisheries and food production in the sea, and concerted attacks on hitherto little studied regions.

Ionospheric Electron-Density—Height Profiles

Material for this report was furnished by E. R. Schmerling of Pennsylvania State University.

For many years a large number of stations, widely dispersed over the world, have been sounding the ionosphere—the electrically charged region of the atmosphere which reflects radio waves—and recording the results. The most widely used method is to send pulsed radio signals vertically upward. The time-delay of the echo of each pulse from the ionosphere is shown on an oscilloscope. A photographic record of the oscilloscope trace relates the heights of the echoes to the different radio frequencies used. Such a record is called an ionogram.

Customarily, only several easily-obtained descriptive characteristics of the ionosphere are obtained from the ionograms. Use of these characteristics in the prediction of the most suitable radio frequencies for communication purposes has been outstandingly successful. The values obtained from ionograms are regularly published by national organizations—in the United States, for example, by the Central Radio Propagation Laboratory (CRPL) of the National Bureau of Standards.

Measurement of Ionograms

Ionograms show the virtual heights of reflection of radio pulses of different frequencies. The virtual height, by definition, is the time between the transmission of a pulse and its return, multiplied by half the velocity of light in free space. Since radio pulses do not travel in the ionosphere with this velocity, the virtual height is generally very different from the true height of reflection.

Reflection is due to the presence of free electrons in the ionosphere; at the reflection point, the electron density is related to the radio frequency of the reflected pulse. If the true height of reflection can be found from the ionogram, the ionogram will provide a profile of electron density at different heights. Such profiles give a very detailed picture of the ionosphere. They are of great value to the radio physicist, for with more precise knowledge of how the ionosphere behaves, he can better formulate and test theories of its origin and character.

The processes which affect the electron densities in the ionosphere can be classified as electron-production (mainly resulting from solar radiation), electron-loss (recombination and molecular attachment) and electron-drift (owing to winds of tidal and electrodynamic origin). These processes are imperfectly understood.

Most previous work has been based on the critical frequencies (the maximum frequency reflected by a given ionospheric layer) and on the minimum virtual heights of the various ionospheric strata, or layers. These are easily measured from the ionograms, but give very incomplete information. The critical frequencies give electron densities at the peak densities of the layers but do not specify their heights. The minimum virtual heights are of uncertain significance as they are determined as much by the underlying ionization as by the true lower boundaries of the layers. Since the production, loss, and drift rates are extremely dependent on height, and since considerable movement of the layers takes place, the height specification is of great importance.

Electron-Density Profiles

The reduction of ionograms to electron-density profiles is mathematically a complicated problem. It is like deducing the contour of a hill from observations of the time needed for a ball, after one push, to roll up one side and down again. As far back as 1930, the physicist de Groot showed that the two problems are formally identical if the effect of the earth's magnetic field is neglected. If the effect of the earth's mag-

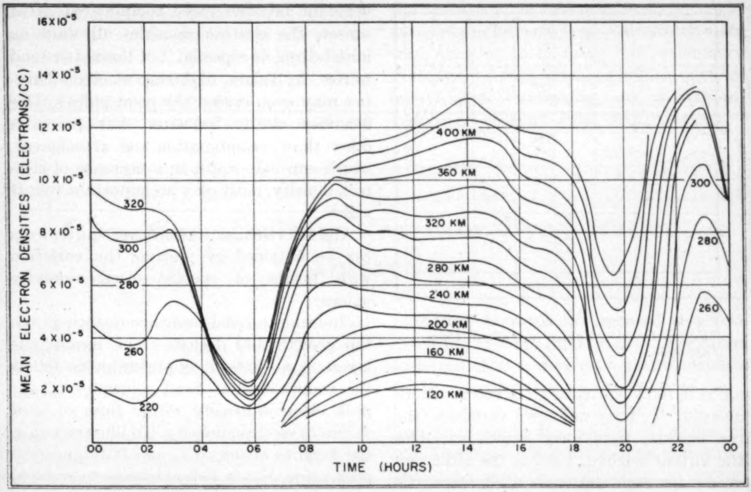

Fig. 3. *Daily Mean Electron Densities at Talara, Peru, During July 1957*

netic field is included, the problem is even more complicated.

Important work has been done by J. M. Kelso, who, while at Pennsylvania State University, devised a rapid but approximate method of solution. Several more precise methods of solution are now available. A matrix method devised by the British scientist K. G. Budden (1955) includes the effect of the earth's magnetic field and determines the profile without making assumptions concerning the profile shape; it is assumed, however, that the electron concentration does not decrease with altitude. (This condition does not usually hold everywhere in the ionosphere, but the assumption can be assessed in using the method, and is generally found to be of minor importance.)

IGY Program

During the IGY, data-reduction programs have been set up in England and the United States. The two programs give reasonable global coverage and lay the foundations for a world-wide survey. For the US program, under the supervision of E. R. Schmerling ionograms are being selected from the following four stations: Washington, D. C.; Talara, Peru; Canal Zone; and Huancayo, Peru. Records are reduced at the Pennsylvania State University for every hour of the three Regular World Days and the 10 magnetically quietest days of each month. This is actually a very small selection from the available data. However, the program is a minimum one aimed at determining electron density behavior so that ionospheric theories may be formulated and tested. Recently, another program of reduction of ionograms for true heights was initiated at CRPL, in Boulder, Colorado. It is directed toward providing electron-density profiles of the ionosphere at locations where radio signals from satellites are observed after propagation through the ionosphere.

"Forty-by-forty matrices" have been developed at Pennsylvania State University for the reduction process. These matrices are arrays of the numerical coefficients con-

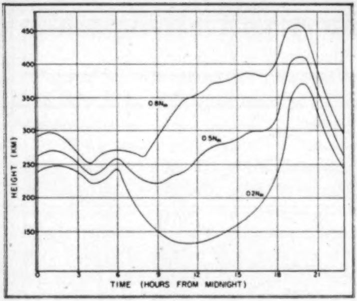

Fig. 4. *Variation With Height of Specific Electron-Density Values at Talara, Peru, July 1957.*

tained in forty equations to be solved simultaneously for forty unknown variables (the true heights) from forty known variables (the virtual heights). Used in the reduction process for each station is a characteristic matrix that depends on the magnetic field at that location. Development of the matrices is being carried out on the University's digital computer, PENNSTAC. Measurement of the virtual height of the ionograms at specific frequencies by scaling is performed manually in 10–15 minutes per record; the computer then performs the reduction in approximately one minute, and prints out true-height values for specified values of electron density.

Preliminary Results

For survey purposes, it is useful to average out some of the day-to-day fluctuations. This can be done conveniently by reading off the electron densities from the profiles at 20-km height intervals, and averaging these over all of the days in each month. The mean curve for Talara produced in this way for July 1957 is illustrated in Figure 3. These curves have several features in common, but they also show some striking differences. Near sunrise, the electron densities increase rather rapidly at all heights, as would be expected. At night, however, the behavior becomes more complicated. Near sunset, the electron densities all show an initial drop, as expected, but thereafter tend to rise. At Talara, nighttime electron densities may even exceed the noon values. This behavior clearly indicates that processes other than recombination and attachment, which can only result in a decrease of electron density, must play an important role at night.

A good visualization of layer movements can be obtained by plotting the variation with height of specific electron-density values.

(In order to avoid confusion resulting from the growth and decay of the ionospheric layers as a whole, it is preferable to follow the movements of fixed multiples of the peak electron density rather than of fixed values of electron density. To illustrate this, the heights of 0.8, 0.5, and 0.2 times the peak value, N_m, at Talara have been graphed with respect to time in Figure 4).

The mean curves that result characterize the height movements, and their spacing provides a measure of the thickness of the ionospheric layer. It is seen that the bulk of the ionosphere is lower by day than at night. An empirical explanation of the nighttime increase of electron density is also immediately apparent, since the thickness decreases markedly. The nighttime increase is thus due to compression of the ionosphere rather than to a nocturnal source of ionization with a peculiar geographical distribution.

It is pertinent to inquire into the differences of behavior at the four stations. These have been chosen quite close to the 75°W meridian, but with widely different geographic and geomagnetic latitudes. The differences of behavior are, in fact, closely linked with the local magnetic dip, as shown by Sir Edward Appleton of the United Kingdom in 1950 and 1954. A natural explanation is found in terms of electrodynamic movements, since tidal winds acting on charged particles produce electron movements that are profoundly influenced by the local inclination of the magnetic field. This was pointed out by D. F. Martyn of Australia in 1947. While the details are still obscure, the general effects are fairly clear.

No more than a start has been made on the provision of electron-density—height data on a sufficiently large scale. Much more work remains to be done, but preliminary evaluation of data already available is yielding valuable information and guiding investigators to some of the right questions.

Deep Core Drilling Program: Byrd Station, Antarctica

The following report is based on material supplied by J. A. Bender, Chief, Snow and Ice Branch, SIPRE. The drilling program was carried out by glaciologists E. W. Marshall, Project Leader, R. W. Patenaude, and A. C. Gow; Chief Driller was J. B. Tedrow.

During the summers of 1956 and 1957, the US Army Snow, Ice and Permafrost Research Establishment (SIPRE) conducted drilling operations at its experimental station on the Greenland Ice Cap. (See *Bulletin No. 7, January 1958*). Although the Greenland drillings produced valuable glaciological and climatological data, their primary purpose was to develop techniques for drilling and core removal in ice.

These techniques were used at IGY Byrd Station in the Antarctic during the 1957–58 summer season to obtain 4-inch cores to a depth of 1013 ft. While the hole was not as deep as that drilled in Greenland in 1956, the core samples recovered are formed of snow of much greater age. (The ice at the 1000-ft level at Byrd Station is formed from snow which fell about 1400 years ago. The age of the deepest core from Greenland is about 950 years. The difference follows from the relatively light precipitation in the Antarctic.)

Drilling Methods

The core drilling at IGY Byrd Station was accomplished with equipment and techniques similar to those employed in coring rock. Major exceptions were the bits, core catchers, drilling fluid, and a specialized core-feed device developed to compensate for the fragility of the ice to be cored.

Previous experience had shown that very low bit pressures are required for drilling in ice. Therefore, all of the drilling and coring was done with the drill string in tension. But the rate of feed became irregular as the weight of the drill string increased with depth. To correct this, a hydraulic core-feed device capable of very fine adjustment was developed, making possible a perfectly constant rate of feed.

In order to prevent the ice from shattering while coring, it was necessary to control the rotation speed of the bit and the rate of penetration within narrow margins and to hold vibration of the core barrel and bit to a minimum. The success of the measures used is shown by the fact that 98% of the core was recovered in usable condition.

Cold compressed air under a pressure of 60 lbs/in^2 was used as the drilling fluid. The temperature of the compressed air varied with the temperature of the outside air but was always kept well below freezing. In the permeable upper layers of the snow, the air tended to dissipate into the snow instead of circulating; as a result, the cuttings adhered to the hole wall or fell back down the hole. This difficulty was solved by casing the drill hole to a depth of 115 ft, where the snow was sufficiently impermeable to maintain air circulation.

Table 3. Mean Deep-Core Densities

Depth (In meters from surface)	*Density (gm/cm^3, ± 0.005 cm)*
18.50–19.00	0.599
(60.3′) 19.00–20.00	0.606
20.00–21.00	0.608
21.00–22.00	0.613
22.00–23.00	0.619
23.00–24.00	0.630
24.00–25.00	0.638
25.00–26.00	0.643
26.00–27.00	0.653
27.00–28.00	0.655
28.00–29.00	0.660
29.00–30.00	0.673
30.00–31.00	0.676
31.00–32.00	0.684
32.00–33.00	0.689
33.00–34.00	0.695
34.00–35.00	0.699
35.00–36.00	0.704
36.00–37.00	0.710
37.00–38.00	0.715
38.00–39.00	0.723
39.00–40.00	0.724
40.00–41.00	0.732
41.00–42.00	0.736
42.00–43.00	0.738
43.00–44.00	0.746
44.00–45.00	0.743
45.00–46.00	0.750
46.00–47.00 (150′)	0.757

Table 4. Densities of Spot Samples

Depth (Meters)	*Density (gm/cm^3, ± 0.005 cm)*
123.00 (400′)	0.885
150.00	0.890
173.00	0.895
200.00	0.899
222.00 (721.5′)	0.905

Analysis of Cores

Close inspection of the early cores revealed a detailed stratigraphic sequence. Alternating layers of coarse- and fine-grained snow were associated with thin ice bands (4 mm) at regular intervals in the cores. Thick bands of ice, indicative of pronounced thaws such as would occur in summer on a temperate zone glacier, were not recognized. However, it is hoped that a detailed density analysis of successive layers in the stratigraphic sequence will permit investigators to distinguish between summer and winter snows and to determine the extent of yearly accumulation.

Work at Byrd Station: The ice cores were placed in a trough and viewed from above with the aid of a light source placed under the trough. The exact positions of ice layers were determined by use of a measuring tape laid along one edge of the trough. The nature of the layers (whether coarse, fine, or icy) was also recorded. Successive sections of the core were then photographed. This combined stratigraphic-photographic procedure was begun on cores taken from the 60.3-ft (18.36-m) level and continued on cores down to the 319.5-ft (97.38-m) level. The photographs were mounted in order on cardboard sheets to give a running stratigraphic column through this interval. Distinctive layering could be observed in cores from depths down to 400 ft. Below this, the cores were homogeneous and visible stratification disappeared, with the exception of the thin ice bands; these persisted to the bottom of the drill hole.

Determinations of the density of individual layers were started using cores from the 60.3-ft level (18.36-m) and completed to 154.4 ft (47.06-m). These determinations were made in the time available at IGY Byrd Station. In all, densities were calculated for 700 core segments ranging in length from 15 cm to slightly less than 1 cm.

Mean densities of 1-m increments have also been calculated; these are presented in Table 3. Densities were also determined for spot samples selected at depths of 123 m, 150 m, 173 m, 200 m, and 222 m (Table 4). The density of the sample from the 222-m depth approaches the maximum value for ice, 0.917. Thin sections were made from the same samples and examined under the microscope for grain-size differences. There was insufficient time to carry out detailed fabric studies of the thin sections while at Byrd Station.

The core from a 3-in, hand-augered hole sunk to a depth of 71 ft (21.6 m) was similarly treated. Densities from 176 segments were determined for the first 30 ft and mean densities for 1-m increments were calculated (see Table 5).

Work at SIPRE: At the outset of drilling

Table 5. Mean Densities of Hand-Augered Cores

Depth (In meters from surface)	*Density (gm/cm³, ± 0 .005 cm)*
2.32–3.00	0.449
3.00–4.00	0.405
4.00–5.00	0.421
5.00–6.00	0.432
6.00–7.00	0.487
7.00–8.00	0.515
8.00–9.00	0.526
9.00–9.37	0.536

at IGY Byrd Station it was intended to split the 4-in cores lengthwise. One half was to be returned to SIPRE, at Wilmette, Illinois, for further research and the other half was to be retained at Byrd Station for use in further studies in the Antarctic. However, because of the large amount of detailed stratigraphy in cores from depths down to 400 ft, it was decided to keep cores from this section of the drill hole in their original state. Splitting of cores from the lower 600 ft was begun, but because of failure of the band saw, cores from the lowest 160 ft remained uncut. Both of the uncut core sections, half the longitudinally split cores, cores from the 71-ft auger hole, and cores from two shallower holes at IGY Byrd Station were transported from the Antarctic aboard the USS *Glacier*. The cores were maintained at 0°F throughout the trip to Boston, where they were unloaded and transported by refrigerated truck to the SIPRE laboratories at Wilmette.

Further research at Wilmette will include the completion of the density profile, grain-size and petrofabric studies, analysis of enclosed foreign particles, measurement of gas-bubble pressure, chemical analysis of entrapped gas, and measurement of tritium and other radioactive substances. Measurement of the ratios of oxygen isotopes 16 and 18 will be carried out at the California Intitute of Technology.

Table 6. Drill-Hole Temperatures

Depth	*Average Temperature (°C. ± 0.10)*
50′	−27.92
100′	−27.95
150′	−27.98
200′	−28.14
250′	−28.26
300′	−28.29
350′	−28.31
400′	−28.39
450′	−28.42
500′	−28.40
550′	−28.40
600′	−28.46
650′	−28.46
700′	−28.51
750′	−28.52
800′	−28.52
850′	−28.53
900′	−28.55
950′	−28.59
1000′	−28.59

Note: Temperatures continue to decrease with depth.

Temperature Measurements

Temperature measurements were made in the deep drill hole to a depth of 1000 ft (Table 6) using a 100-ohm thermohm and a Wheatstone bridge temperature indicator.

Thermal conditions in the hole were disturbed by the drilling and by the cold compressed air used as the drilling medium. Therefore, temperature measurements were not begun until three days after completion of the drilling. This allowed the hole to return to thermal equilibrium.

The thermohm was read at 50-ft intervals. It was given a minimum of two hours at each level to come to equilibrium. Instrument errors, reading errors, and the disturbed thermal conditions from the effects of drilling permit an accuracy of ±0.10°C.

Because steel casing was set to a depth of 115 ft, temperatures taken within this upper zone may be subject to errors greater than ±0.10°C.

Progress of the Moonwatch Program

Material for this report was furnished by Leon Campbell, Jr., and Armand Spitz of the Smithsonian Astrophysical Observatory.

Plans for optical tracking of IGY artificial satellites, under the direction of the Smithsonian Astrophysical Observatory, anticipated two phases. Immediately after a launching, the Moonwatch teams of the volunteer visual observation program, using low-power, wide-field telescopes, would search for the satellite. Once the satellite had been located, or "acquired," and its orbit computed, optical tracking would be carried on by the large tracking cameras (see "Optical Tracking of Earth Satellites," *Bulletin No. 12*). However, when the USSR satellites were launched, Moonwatch teams necessarily carried on the visual tracking program until the full complement of tracking cameras could be put into operation.

A measure of the value of Moonwatch teams in the satellite visual observing program is the number of scientifically useful observations produced. Not only have Moonwatch teams provided a great number of observations but the observations cover all the satellites launched to date. With these data, together with the radio tracking data provided by the Naval Research Laboratory, it has been possible for the Smithsonian Astrophysical Observatory to compute preliminary ephemerides that have been used to position the satellite tracking cameras at the IGY precision tracking stations. Furthermore, Moonwatch observations provided almost daily have been utilized in the constant refining of these ephemerides.

Results

There are approximately 230 Moonwatch stations in various parts of the world. Eighty per cent of these stations have contributed observational data. Many of the stations that have not made observations are among those recently organized.

Through May 9, 1958, observations of scientific value have been reported by 181 teams. In these observations, the positional data were accurate to one degree of arc, the time of observation accurate to one second, and the objects under observation were identifiable as satellites or as orbiting parts of the launching vehicles. The stations made either one observation or a group of observations during a single satellite crossing on 1599 occasions.

The following table shows the total observing occasions, or sessions, credited to teams in the indicated areas of the world:

Area	*1957α*	*1957β*	*1958α*	*1958β*	*1958γ*	*Total*
U.S.	278	523	60	8	18	887
Japan	134	348	6	4	—	492
Africa	23	52	41	2	8	126
Australia	31	36	3	2	—	72
Elsewhere	3	18	1	—	—	22
	469	977	111	16	26	1599

At these observing sessions, the following numbers of separate observations were made: teams in the United States, 2013; Japan, 879; Africa, 256; Asia, 21; Australia, 259; South America, 11; Central America, 4; total 3443.

Throughout the period of visual tracking, Moonwatch observational reports have usually furnished data in a sufficiently constant flow to allow for continual refining of preliminary ephemerides of the several objects in orbit. The world-wide distribution of Moonwatch stations has made this possible; as the visibility areas have shifted around the world, there have generally been teams so located as to be able to continue to observe the satellites.

During the early months of the program, reports from United States teams were received by telephone at the Smithsonian Observatory within a few minutes of the actual observations. Recently, telephone reporting has been discontinued in favor of telegraph. The results, with respect to accuracy and speed of transmissions, compare most favorably. Moreover, telegraphic reporting has allowed conservation of the limited manpower at Moonwatch headquarters. Reports from stations outside continental United States have been transmitted, from the beginning of satellite observing, over commercial cable and over IGY and other communication systems. These facilities, too, have proved satisfactory.

Several days before the demise of 1957β, all Moonwatch teams were called upon to set up groups of 4 or 5 observers each to watch throughout the darkness hours of April 12, 13, and 14, 1958, for its fall. Observations of the satellite were made by the three teams toward the very end of the satellite's last revolution. These reports were as follows: Millbrook, N. Y., on April $14^d01^h45^m35^s$; Bryn Athyn, Pa., $01^h45^m46^s$, and New Haven, Conn., $01^h45^m47^s$, (UT). Within a few minutes of these observations, approximately 15 sightings were made of the dying satellite by ships at sea in the Caribbean, and by thousands of persons on islands in the area. Exactly where the satellite and its fragments fell is not determined, but it was last observed over the sea off the coast of the Guianas.

Future of Program

Continued interest in visual observation of satellites is gratifying because of the great deal of observing that undoubtedly lies ahead. Satellite radios may fail before preliminary ephemerides are determined, and observations will need to be made of the dying moments of satellites. Also, each launching may produce not only a radio-signalling satellite, but one or more orbiting components without radios. To date, there have actually been more objects in orbit without radio transmitters than with them.

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Gravity Formulas Utilizing Correlation with Elevation

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Abstract—Solutions for the first two terms of the standard gravity formula $\gamma_e(1 + \beta \sin^2 \phi)$ were made, all based on the assumption that the gravity anomalies in areas without observations will average the same as observed values of the same elevation. The solution by the method considered theoretically best yields

$$\gamma = (978040.4 \pm 1.3)[1 + (0.0053014 \pm 0.0000030) \sin^2 \phi - 0.0000059 \sin^2 2\phi],$$

and

$$f = 1/298.15 \pm 0.26$$

The coefficients of the fourth and sixth degree zonal harmonics were also computed and used to estimate how much a flattening found from satellite motion would differ. For example, it is estimated that an orbit approximating that of 1958β would give $f = 1/298.00$.

At the Army Map Service, a statistical and harmonic analysis of gravity is being made to take into better account the correlation of the anomalies (1) with topography, and (2) with each other (auto-correlation). The full solution in the form of spherical harmonics will not be completed for some months; however, in view of the interest generated by the flattenings obtained from satellite orbits, a partial solution has been made for a standard gravity formula, utilizing the correlation with topography but neglecting autocorrelation.

In a conventional least-squares solution for a standard gravity formula, a best fit is made to the gravity observations available, combined in some manner, such as 1° × 1° square mean anomalies. In making such a solution, it is implicitly assumed that the gravity anomalies in areas without observations average the same as in areas with observations. Now it is well-known that (1) gravity anomalies have a positive correlation with elevation; (2) the proportionate distribution of elevations of gravity observations differs radically from that of the Earth as a whole, there being an excess of observations on the land as compared with the oceans. These facts are numerically demonstrated by Table 1, which is based on the mean anomalies of 7950 1° × 1° squares.

Table 1 thus indicates that the common assumption, "Gravity anomalies in the unsurveyed areas average zero," is equivalent to the assumption, "Gravity anomalies in the unsurveyed areas average 5.78 mgal higher than in surveyed areas of the same elevation," which sounds less reasonable. The purpose of this paper is to solve for a standard gravity formula with the assumption, "Gravity anomalies in the unsurveyed areas average the same as observed anomalies of the same elevation." 'Unsurveyed area' is defined throughout as any area outside the 1° × 1° squares with observations.

The basic gravity material used is the compilation of 1° × 1° square mean anomalies made by Heiskanen and his assistants at Ohio State University. Only values based on observations within the 1° × 1° square were used; extrapolated or interpolated values were disregarded. In addition, values for 1040 more 1° × 1° squares were obtained from data compiled at the U. S. Navy Hydrographic Office, 130 1° × 1° square means were improved by additional values, and 160 1° × 1° square means at sea were corrected by reduction of the anomaly to the mean elevation of the square. This correction was made not only for squares of more than one observation in the manner described by *Uotila* [1957], but also the average gradient we obtained for 1° × 1° squares at sea, +0.056 mgal/m, was applied to single observations on small islands, etc., to obtain more representative values. Of the additional data, the great majority were observations on the oceans by Worzel and his associates of the Lamont Geological Observatory, and by members of the U. S. Navy Hydrographic Office under supervision of A. L. McCahan.

TABLE 1 - *Mean gravity anomalies of 1° × 1° squares classified by mean elevation*

Depth × 0.62 or elevation[a]	Unobserved areas	Observed areas		
	Portion of Earth's surface	Portion of Earth's surface	Mean anomaly Δg_h	Mean latitude term $\overline{\sin^2 \phi}^h$
ft			mgal	
≧*12,000*	0.0534	0.0018	−49.17	0.2139
11,000	0.0739	0.0045	−14.60	0.1857
10,000	0.0905	0.0132	−12.45	0.1907
9000	0.1110	0.0080	−9.83	0.2119
8000, 7000	0.1441	0.0159	−8.28	0.1845
6000, 5000	0.0635	0.0072	−3.62	0.2402
4000, 3000	0.0246	0.0082	−1.16	0.2072
2000, 1000	0.0252	0.0085	+12.06	0.2662
0	0.0773	0.0342	+3.69	0.4080
1000	0.0308	0.0317	+0.94	0.3791
2000, 3000	0.0799	0.0213	+4.14	0.3724
4000, 5000	0.0236	0.0093	+16.89	0.3319
≧6000	0.0306	0.0078	+40.22	0.3516
	0.8284	0.1716		

Mean anomalies, using Δ*g*'s in 4th column: unobserved areas, −5.78; observed areas, +1.45.

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[a] Italicized values are 0.62 *depth*; height (and depth) values are rounded off to the *nearest* thousand feet.

In latitudes above 50° the 1° × 1° squares were taken to be of more than 1° extent in longitude, in order to maintain approximately equal area: 2° wide from Lat. 50° to 70°; 5° wide, 70° to 80°; 10° to 120° wide, 80° to 90°.

The mean elevations for 1° × 1° squares with observations were obtained from a compilation made in 1952 by the Cincinnati Field Office of the Army Map Service, under supervision of R. F. Van Hart. These elevations were estimated from aeronautical and hydrographic charts averaging 1:1,000,000 in scale. The precision is the nearest 1000 ft; the accuracy is as good as the available maps, except for a few over-estimates in mountainous areas. Since the compilation was originally made for use in isostatic reductions, depths below sea level were multiplied by $(2.67 - 1.03)/2.67 = 0.62$; we have retained these figures in the tables, in order to avoid either a second round-off or non-significant digits.

All solutions were made in terms of nine 10° zones of latitude, the north and the south combined. The portion of each 10° zone falling in each elevation interval was estimated from the 1:10,000,000 Monaco bathymetric charts except for Antarctica, for which the 1:7,000,000 National Geographic Society map was used. For latitudes above 70°, elevations above sea level were assumed supported on the average 20 pct by rock and 80 pct by ice, thus making the mass excess equivalent to $(0.20 + 0.80 \times 1.00/2.67) = 0.50$ times the mass excess for the same elevation on solid rock. A breakdown by elevation also was made at the 1° × 1° squares in each zone, and the mean anomaly Δg_{zh} was computed for each. Table 2 shows the results in terms of Δg_{zh}; r_{zh}, the per cent of the zone represented by Δg_{zh}; s_{zh}, the per cent of the zone of the same elevation without observations; and a_z, the per cent of the total Earth's surface covered by the zone.

The most recent gravity formula computed is that of Heiskanen and Uotila [*Heiskanen*, 1957]

$$\gamma = 978049.6\,(1 + 0.0052934 \sin^2 \phi - 0.0000059 \sin^2 2\phi)$$

$$f = 1/297.4$$

This formula is based on 6679 1° × 1° square mean anomalies; values greater than 75 mgal in absolute value were rejected. In the computations throughout this paper, no values were rejected. Since, as mentioned, we also have considerable additional data for a total of 7950 squares, a conventional least-squares solution was made to serve as a standard of comparison for subsequent changes in method. The mean anomaly for each zone was computed from Table 2 as

$$\Delta g_z = \frac{\sum r_{zh} \Delta g_{zh}}{r_z} \tag{1}$$

These mean anomalies Δg_z are listed in Table 3, together with those of subsequent solutions. Nine observation equations were written

$$v_z = \Delta g_z - (\Delta \gamma_e + \Delta \alpha \sin^2 \phi_z) \tag{2}$$

where $\Delta \gamma_e$ is the correction to the γ_e of the International formula; $\Delta \alpha$, the correction to $\gamma_e \beta$; and $\sin^2 \phi_z$, the mean value of $\sin^2 \phi$ for the zone. Each of these observation equations had a weight of $a_z r_z$. The result is: $\Delta \gamma_e = -1.12$ mgal, or $\gamma_e = 978047.9$ mgal, and $\Delta \alpha = +8.43$ mgal, or $f = 1/297.76$.

Using our rule that gravity anomalies in the unsurveyed areas average the same as observed anomalies of the same elevation, the estimated mean anomaly for each zone will be

$$\Delta g_z = \sum r_{zh} \Delta g_{zh} + \sum s_{zh} \Delta g_h \tag{3}$$

where Δg_h is the mean value for elevation h given in Table 1. The weight of each observation equation now becomes a_z. The Δg_z are again listed in Table 3. The result is: $\Delta \gamma_e = -7.88$ mgal, or

TABLE 2 – *Breakdown of zones by elevation and corresponding mean anomalies*

Depth × 0.62 or elevation[a]	Zone and zone area a_z in per cent of total Earth's surface																										
	0°–10° 17.36 pct			10°–20° 16.84 pct			20°–30° 15.80 pct			30°–40° 14.28 pct			40°-50° 12.32 pct			50°–60° 10.00 pct			60°–70° 7.37 pct			70°–80° 4.51 pct			80°–90° 1.52 pct		
	Δg_{zh}	r_{zh}	s_{zh}	Δg_{zh}	r_{zh}	s_{zh}	Δg_{zh}	r_{zh}	s_{zh}	Δg_{zh}	r_{zh}	s_{zh}	Δg_{zh}	r_{zh}	s_{zh}	Δg_{zh}	r_{zh}	s_{zh}	Δg_{zh}	r_{zh}	s_{zh}	Δg_{zh}	r_{zh}	s_{zh}	Δg_{zh}	r_{zh}	s_{zh}
ft	mgal	pct	pct	mgal	pct	pct	mgal	pct	pct	mgal	pct	pct	mgal	pct	pct	mgal	pct	pct	mgal	pct	pct	mgal	pct	pct	mgal	pct	pct
≧*12,000*	−17.8	0.1	5.1	−91.4	0.2	7.3	−32.3	0.4	6.7	−59.0	0.4	6.9	−5.0	0.1	5.9		0.0	3.2		0.0	1.7		0.0	0.0		0.0	00.0
11,000	−10.0	0.3	7.8	−22.7	0.7	8.5	−18.8	1.1	8.3	−9.7	0.5	10.5	+15.0	0.2	8.9	−5.0	0.1	4.7		0.0	2.9		0.0	0.0		0.0	0.0
10,000	−9.2	1.7	12.7	−14.7	1.7	9.8	−12.3	2.1	8.0	−13.5	2.2	8.0	−7.2	0.6	9.9	−33.3	0.2	9.7		0.0	6.4		0.0	0.9		0.0	6.8
9,000	−12.1	1.1	16.5	−16.9	0.9	12.1	−7.5	1.2	9.5	−13.2	1.2	8.9	+3.4	0.6	11.0	+30.0	0.0	12.6	+20.0	0.0	8.1		0.0	1.4	+8.3	1.8	8.3
8000, 7000	−8.9	2.9	12.9	−17.4	2.5	14.6	+0.6	1.2	16.0	−5.7	1.9	15.2	−4.9	0.7	16.7	+7.4	0.5	18.1		0.0	12.3		0.0	4.1	+3.3	4.5	4.5
6000, 5000	−2.8	0.9	4.8	−0.7	1.0	6.6	−7.4	0.7	5.8	−3.7	1.0	6.6	−5.9	0.8	7.3	−4.4	0.2	7.5	+3.3	0.1	7.7		0.0	5.8	+20.0	0.9	5.5
4000, 3000	−6.7	1.3	1.2	−0.8	1.0	2.7	+11.5	0.8	1.9	+0.7	1.3	1.9	−14.8	0.5	2.7	−5.7	0.2	3.0	+15.0	0.1	4.9	−13.3	0.2	4.3	+20.0	0.9	3.4
2000, 1000	+9.8	0.9	1.5	+6.1	0.8	1.6	+9.1	1.1	1.0	+13.8	1.5	1.0	+8.6	0.6	1.7	+31.4	0.4	3.1	+30.0	0.2	6.4	+36.7	0.6	14.2	+23.3	0.9	4.6
0	+17.7	2.5	7.7	+6.1	1.6	5.9	−1.0	2.8	5.6	+4.4	3.7	5.3	−0.8	5.1	3.6	+2.6	7.1	8.8	+1.9	4.1	14.9	+2.4	2.3	25.5	+60.0	0.6	8.5
1000	+16.4	1.4	4.1	+1.7	1.9	4.0	−10.1	3.6	3.7	+2.0	3.8	0.7	+1.2	6.1	0.0	+4.1	5.9	1.4	+3.1	1.5	7.6	−0.3	1.0	5.8	−40.0	0.2	7.4
2000, 3000	+3.8	0.7	7.7	+6.9	1.5	9.2	+1.3	2.6	10.0	+7.9	3.0	3.6	+3.6	4.1	4.7	+1.0	2.9	7.1	+2.5	1.4	11.9	+5.5	0.3	13.3		0.0	14.6
4000, 5000	+10.6	0.9	1.2	+24.8	0.3	1.8	+20.4	1.1	1.2	+17.9	1.6	1.6	+19.7	1.7	2.7	−4.8	0.8	1.2	+7.3	0.3	2.9	+39.1	0.3	11.8		0.0	14.6
≧6000	+59.6	0.4	1.9	+84.2	0.3	1.6	+43.1	0.8	2.7	+29.9	1.9	5.6	+40.9	1.8	1.9	+21.2	0.2	1.0	+45.0	0.1	4.7		0.0	8.4		0.0	12.0
Total, pct of zone		15.3	84.7		14.2	85.8		19.4	80.6		24.1	75.9		22.8	77.2		18.6	81.4		7.9	92.1		4.9	95.1		9.8	90.2
		r_z	s_z		r_z	s_z		r_z	s_z		r_z	s_z		r_z	s_z		r_z	s_z		r_z	s_z		r_z	s_z		r_z	s_z

Note: Δg_{zh} = mean anomaly for zone and elevation; r_{zh} = observed portion in per cent of zone; s_{zh} = unobserved portion in per cent of zone.

[a] Italicized values are 0.62 *depth*; height (and depth) values are rounded off to the *nearest* thousand feet.

TABLE 3 – *Estimated mean anomalies of zones*

Zone	Estimate reference flattening			
	None (conventional solution)	1/297.0	1/297.3	1/302.6
°	mgal	mgal	mgal	mgal
0–10	+2.54	−5.94	−6.62	−18.3
10–20	−4.18	−7.51	−8.02	−16.8
20–30	−1.67	−6.26	−6.45	−9.8
30–40	+2.71	−4.69	−4.46	−0.5
40–50	+5.09	−5.29	−4.60	+7.3
50–60	+2.82	−4.39	−3.24	+16.6
60–70	+3.71	+0.32	+1.96	+30.3
70–80	+7.86	+8.07	+9.97	+42.8
80–90	+11.21	+7.53	+9.59	+45.1
Solution flattening	1/297.76	1/297.90	1/298.15	1/302.6
Solution $\Delta\gamma_e$	−1.12	−7.88	−8.56	−20.8

$\gamma_e = 978041.1$ mgal, and $\Delta\alpha = +9.99$ mgal, or $f = 1/297.90$.

However, the anomalies used in computing the Δg_s are with reference to the International formula flattening of 1/297; if a standard formula of different flattening had been used, the estimated anomalies for the unknown areas would change, and a different solution would be obtained. Let the anomaly with respect to a standard formula differing from the International be

$$\Delta g = g_0 - [\gamma_e + \alpha_j \sin^2 \phi] \tag{4}$$

then with respect to the International formula it will be

$$\begin{aligned} \Delta g_i &= g_0 - [\gamma_e - \Delta\gamma_e + (\alpha_j - \Delta\alpha_j) \sin^2 \phi] \\ &= \Delta g + \Delta\gamma_e + \Delta\alpha_j \sin^2 \phi \end{aligned} \tag{5}$$

The estimate obtained from a sample of n anomalies with respect to the International formula then will be

$$\begin{aligned} \text{Est. } \widehat{\Delta g}_h &= \frac{1}{n} \sum \{\Delta g + \Delta\gamma_e + \Delta\alpha_j \sin^2 \phi\} \\ &= \Delta g_h + \Delta\alpha_j \overline{\sin^2 \phi^h} + \Delta\gamma_e \end{aligned} \tag{6}$$

where $\overline{\sin^2 \phi^h}$ is the mean $\sin^2 \phi$ for the sample. The anomalies (6) are what we get from our data; they are the values in Table 1. If the estimates are being made with reference to a different flattening from 1/297, we want the anomalies (5). Hence in any observation equation using an estimated zone mean anomaly based on data from other latitudes, there should be added a correction equal to (5) minus (6), that is

$$\Delta\alpha_j(\sin^2 \phi_s - \overline{\sin^2 \phi^h}) \tag{7}$$

The $\overline{\sin^2 \phi^h}$ values are shown in the last column of Table 1.

We have the following possibilities for alternate flattenings to which to refer the estimated zone mean anomalies: (1) the flattening which minimizes the correlation of the Δg_{sh} with latitude; (2) the flattening of hydrostatic equilibrium, 1/297.34 [*Bullard*, 1948]; and (3) the flattening of the solution itself.

To determine the flattening which minimizes the correlation of Δg_{sh} with latitude, separate solutions were made in the conventional manner for each of seven elevation groups, and the results combined with weights in proportion to the occurrence of each elevation on the total Earth's surface. The results are shown in Table 4.

The resulting flattening of 1/297.33 is remarkably close to the flattening of hydrostatic equilibrium. This agreement may be significant; it certainly seems logical that correlation of the gravity anomaly with elevation should be a function of departure from the hydrostatic figure.

For the minimum correlation and hydrostatic flattening, $\Delta\alpha_j = -(1/297.3 - 1/297.0)978049 = +3.36$ mgal, and

$$\Delta g_s = r_s \Delta g_0 + \sum s_{sh} [\Delta g_h + 3.36 (\sin^2 \phi_s - \overline{\sin^2 \phi^h})] \tag{8}$$

The Δg_s are again shown in Table 3. The solution: $\Delta\gamma_e = -8.56$ mgal, or $\gamma_e = 978040.4$ mgal, and $\Delta\alpha = +12.70$ mgal, or $f = 1/298.15$.

For Method 3, in which the estimated zone mean anomalies are referred to the flattening of the solution itself, $\Delta\alpha_j = \Delta\alpha$, and so must remain as an unknown in the observation equations, which become

$$\begin{aligned} v_s = {} & r_s[\Delta g_0 - (\Delta\gamma_e + \Delta\alpha \sin^2 \phi_s)] \\ & + \sum_h s_{sh}[\{\Delta g_h + \Delta\alpha(\sin^2 \phi_s - \overline{\sin_2 \phi^h})\} \\ & - \{\Delta\gamma_e + \Delta\alpha \sin^2 \phi_s\}] \\ = {} & r_s \Delta g_0 + \sum_h s_{sh} \Delta g_h - \Delta\gamma_e \\ & - \Delta\alpha(r_s \sin^2 \phi_s + \sum_h s_{sh} \overline{\sin^2 \phi^h}) \end{aligned} \tag{9}$$

The result is: $\Delta\gamma_e = -20.8$ mgal, or $\gamma_e = 978028.2$ mgal, and $\Delta\alpha = +61.4$ mgal, or $f = 1/302.6$.

The Δg_s computed after the solution using $\alpha_j = +61.4$ mgal are shown in Table 3.

It seems evident from the unreasonably large change yielded by Method 3 that correlation of the gravity anomaly with elevation is not a function of departure from the mean Earth ellipsoid, the best fit to the geoid which is the traditional objective of geodesy. This conclusion suggests that though 1/298.15 is the flattening which best fits the external gravitational field, the best geophysical reference might be one with the hydrostatic flattening 1/297.34. Assuming that the mean attraction should remain the same, the equatorial term for this 'geophysical' standard formula would be

$$\gamma_e = 978040.4 \quad [1 + \tfrac{1}{3}(1/297.34 - 1/298.15)]$$
$$= 978045.9 \text{ mgal.}$$

A corroboration of this difference between the hydrostatic and external field flattenings was found by fitting a straight line formula, $\Delta g = a + bh$, to the Δg_h in Table 1, weighting each in proportion to the occurrence of its elevation on the total Earth's surface. The best fit was $\Delta g = +13.17 + 2.44h$ mgals, for h in thousands of feet, or $+13.17 + 0.0080h$ for h in meters. Assuming that this correlation applies to the second degree zonal harmonic of the topography, as found by *Prey* [1922], we get for the corresponding coefficient of gravity

$$0.0080(1134 - 1037 \times 1.03/2.67) = +5.88 \text{ mgal,}$$

$$\text{or} \quad \Delta f = -3/2 \cdot 5.88/978049 = -0.0000090;$$

$$\text{while } 1/298.15 - 1/297.34 = -0.0000092.$$

To evaluate the accuracy of the solution, we must consider the two reasons why the estimated zone mean anomalies differ from 0: (1) because the true zone mean will differ from 0; and (2) because the estimate will differ from the true zone mean. The first difference is due to the higher degree zonal harmonics $P_n(\sin\phi)$ in the gravitational field. An estimate was made of the variances of the harmonic degrees by a covariance analysis; the portion of each variance due to the zonal harmonic was assumed to be $1/(2n + 1)$; and the variances of the zone means were then computed as $\Sigma\sigma^2{}_n[\overline{P_n(\sin\phi)_z}]^2$ using the even degrees only, since the odd degrees cancel each other out in meaning the northern and southern hemisphere zones. The resulting element variances $\sigma^2\{\Delta g_z\}$ are given column 2 of Table 5.

TABLE 4 - *Gravity formula solutions by elevation groups*

Depth × 0.62 or elevation*	Portion of total	$\Delta\gamma_e$	$\Delta\alpha$	f
ft		mgal	mgal	
≧*10,000*	0.2373	−17.07	+3.49	1/297.32
9000–7000	0.2790	−12.82	+20.80	1/298.89
6000–3000	0.1035	−2.13	−0.92	1/296.92
2000–0	0.1452	+8.45	−8.20	1/296.26
1000	0.0625	+0.09	+2.34	1/297.21
2000, 3000	0.1012	+6.34	−3.60	1/296.67
≧4000	0.0713	+35.08	−19.36	1/295.26
Weighted means		−3.47	+3.69	1/297.33

Italicized values are 0.62 *depth*; height (and depth) values are rounded off to the *nearest* thousand feet.

TABLE 5 - *Variances of 10° zone means*

Zone	Element variance $\sigma^2\{\Delta g_z\}$	Estimate variance $\sigma^2\{\hat{\Delta g_z} - \Delta g_z\}$	Total	$\frac{0.75}{a_z}$
° °	mgal²	mgal²	mgal²	
0–10	2.4	1.3	4	4.3
10–20	2.7	1.4	4	4.4
20–30	3.3	1.3	5	4.7
30–40	3.6	1.4	5	5.2
40–50	4	1.6	6	6.1
50–60	5	2.1	7	7.5
60–70	7	3.3	10	10.1
70–80	12	5.8	18	16.1
80–90	36	15.8	52	49.6

The estimate variances $\sigma^2\{\widehat{\Delta g_z} - \Delta g_z\}$ were estimated on the assumption of randomness between 10° blocks, which is incorrect, but consistent with the assumption of randomness between 10° zones already made in the least-squares solutions. Using the 10° block system of ***Zhongolovich*** [1952], the portion of each block observed was computed. The variances of the anomaly estimates based on elevations were computed for (1) a sample of all the 1° squares; and (2) a sample of all 10° squares more than 70 pct observed. The former variance was found to be about 1000 mgal²; the latter, 110 mgal². Thus, for example, for a zone consisting of 7200 1° squares, the contribution of a single 1° × 1° square estimated anomaly to the zone variance would be $1000/(7200)^2 = 1/52{,}000$ mgal²; but for a 10° × 10° square estimated anomaly the contribution would not be 100/52,000, but $110/(72)^2 = 1/47$ mgal². For cases in between the one and 70 pct unobserved, values were interpolated for the variance $\sigma^2\{\Delta g_s\}$, where the s denotes the portion of the 10° square unobserved. The total estimate variance, then, for a zone of n 10° blocks will be $(1/n^2)\Sigma_i s_i^2\sigma_i^2\{\Delta g_s\}$. This solution assumes, of course, that the contribution of 1° × 1° squares with gravity observations is negligible.

The estimate variances for each zone are given in the 3rd column of Table 5.

Knowing the variances of the zone means Δg_z, we thus can compute the variances of the $\Delta\gamma_e$ and $\Delta\alpha$ derived from them; for example, expressing $\Delta\gamma_e$ as $\Delta\gamma_e = \sum c_z \Delta g_z$, then

$$\sigma^2\{\Delta\gamma_e\} = \sum c_z^2 \sigma^2\{\Delta g_z\}.$$

The zone variances were computed with the purpose of using them for weighting; however, note that they are almost inversely proportional to the zone areas; so nearly so, that the change from weighting according to area would make negligible difference.

The flattenings obtained from terrestrial gravimetric observations are not directly comparable to those obtained from the precession of satellite nodes, because the satellite passes through only a portion of the Earth's gravitational field and hence will give a best fitting answer for only this portion. If we know the higher zonal harmonics of even degree, we can estimate the difference of a flattening derived from satellite observations. The coefficient for a zonal harmonic of degree n will be

$$a_n = (2n+1)\int_{-\pi/2}^{\pi/2} \Delta g_z P_n\{\sin\phi\}\cos\phi\, d\phi \quad (10)$$

where Δg_z is the mean anomaly for the infinitesimal zone $d\phi$. The zonal harmonics a_4 and a_6 were computed from the Δg_z based on $f = 1/297.3$ (see Table 3), using as a unit of area the 10° square of *Zhongolovich* [1952], and using his averaged harmonics $\overline{P_n}$

$$a_n = \frac{2n+1}{410}\sum_z n_z \Delta g_z \overline{P_n}(\sin\phi_z) \quad (11)$$

where n_z is the number of 10° blocks in each zone: 72 in 0°–10°, 68 in 10°–20°, etc. The values found:

$$a_4 = +5.05 \text{ mgal};$$

$$a_6 = +3.40 \text{ mgal}.$$

A spherical harmonic component of the gravitational acceleration on the geoid of degree n will have a corresponding acceleration at altitude $h = r - R$ which is $(R/r)^{n+2}$ times as great, where R is the Earth's radius. For terms of interest in the present problem

$$a_{2.h} = (R/r)^4 a_2, \qquad a_{4.h} = (R/r)^6 a_4,$$

$$a_{6.h} = (R/r)^8 a_6 \quad (12)$$

The apparent change $\delta a_{2.h}$ in the second-degree harmonic coefficient from measurements, direct or indirect, of the gravitational field limited to a zone should be the best least-squares fit of the second-degree harmonic to the higher degree even zonal harmonics in the zone. For altitude h between latitudes $+\phi_i$ and $-\phi_i$ we therefore have

$$\frac{d}{d(\delta a_{2.h})} \cdot \left(\int_{-\phi_i}^{+\phi_i} [\delta a_{2.h} P_2 - (a_{4.h} P_4 + a_{6.h} P_6 + \cdots)]^2 \cos\phi\, d\phi\right) = 0$$

or

$$\int_{-\phi_i}^{+\phi_i} P_2[\delta a_{2.h} P_2 - (a_{4.h} P_4 + a_{6.h} P_6 + \cdots)] \cdot \cos\phi\, d\phi = 0 \quad (13)$$

The integrals being symmetrical about the equator, we can set

$$\delta a_{2.h} = \frac{a_{4.h}\int_0^{\phi_i} P_2 P_4 \cos\phi\, d\phi + a_{6.h} \cdot \int_0^{\phi_i} P_2 P_6 \cos\phi\, d\phi + \cdots}{\int_0^{\phi_i} [P_2]^2 \cos\phi\, d\phi} \quad (14)$$

or

$$\delta a_{2.h} = A(\phi_i) a_{4.h} + B(\phi_i) a_{6.h} + \cdots$$

$$\left(\frac{R}{r}\right)^4 \delta a_2 = A(\phi_i)\left(\frac{R}{r}\right)^6 a_4 + B(\phi_i)\left(\frac{R}{r}\right)^8 a_6 + \cdots$$

$$\delta a_2 = A(\phi_i)\left(\frac{R}{r}\right)^2 d_4 + B(\phi_i)\left(\frac{R}{r}\right)^4 a_6 + \cdots \quad (15)$$

$A(\phi_i)$ and $B(\phi_i)$ are functions of the orbital inclination only, while r is a function of the eccentricity and semi-major axis. To solve the problem we need merely the inclination and the mean values of $1/r^2$, $1/r^4$, $\cdots$ for the period of time from which the determination of flattening was made.

For example, for a satellite of inclination 34°, semimajor axis 8650 km and eccentricity 0.19, we get $A(\phi_i) = -0.414$, $B(\phi_i) = +0.092$, and mean $1/r^2 = 1/(8.56)^2$ in units of 1000 km. Using the values $a_4 = +5.05$ mgal and $a_6 = +3.37$ mgal, $\delta a_2 = -1.16 + 0.09 = -1.07$ mgal. Whence $\Delta\alpha = -1.61$ mgal, or $\Delta f = +0.00000165$, and $f = 1/298.00$

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A Study of the Use of Atmospheric-Electric Measurements in Fog Forecasting

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Abstract—A statistical study of atmospheric-electric and pertinent meteorological data collected in Argentia, Newfoundland, from January through September 1955, shows that fogs produce a decrease in the electrical conductivity with a concurrent increase in potential gradient. A quantitative analysis of the data shows that during fog (horizontal visibility less than ½ mile, ceiling less than 200 ft) the average conductivity was less than 0.65 times the monthly mean 92 pct of the time and the average potential gradient was more than 2.0 times the monthly mean 87 pct of the time. From one to two hours preceding the onset of fog the conductivity decreased and the potential gradient increased in about 70 pct of the events. One hour prior to dissipation of fog conductivity increased and potential gradient decreased in 75 pct of the events. Similar studies should be made in additional areas to determine whether the Newfoundland results are unique or may be encountered more generally.

Introduction—The lowering of the electrical conductivity of the atmosphere in thick fog has been reported by several authors; notably, *Gockel* [1917], and *Scrase* [1933]. *Reiter* [1956] working in the northern Bavarian Alps reported, "Certain rules were derived pertaining to the forecast of formation, dissolution, and stability of fog and stratus from the behavior of the electric magnitudes."

George [1951] gives the following definition of fog: "When a cloud consisting of minute water droplets or ice crystals envelops the observer and restricts his horizontal visibility to 1000 m or less, the international definition of fog has been satisfied." For purposes of this paper the definition of fog is further restricted to conditions in which the horizontal visibility is less than ½ mile and the ceiling is less than 200 feet. These restrictions coincide with minimum meteorological conditions for the landing and take-off of aircraft at the U. S. Naval Station, Argentia, Newfoundland.

Of the atmospheric-electric quantities, conductivity is the most important index of local variations. The atmospheric conductivity is due chiefly to small ions which are produced by cosmic radiation and by radioactive matter in the Earth and air. The presence of contaminants, plentiful in continental air masses, causes the small ions to lose their charge to less mobile nuclei, thereby reducing the conductivity. Hence local pollution sources and meteorological conditions determine the conductivity within the exchange (or mixing) layer, and cause a local diurnal variation in conductivity which corresponds to the daily turbulence cycle [*Sagalyn*, 1956].

Potential gradient is an important index of world-wide effects. *Mauchly* [1926] found that the surface potential gradient over the oceans at different longitudes varies diurnally with universal time. *Whipple* [1929] later showed that this universal diurnal variation with a maximum at 19h GMT correlates with a similar one in world-wide thunderstorm activity. The diurnal variation in potential gradient at land stations is more complex, the local variations due to conductivity changes frequently obliterating the universal variation.

In 1954, the U. S. Naval Research Laboratory originated a research program to evaluate atmospheric-electric measurements in terms of universal and local effects and to correlate these measurements with meteorological phenomena. Several stations were established to make continuous measurements of atmospheric-electric quantities. The U. S. Naval Station, Argentia, Newfoundland, was chosen as a site for one of the stations because of its climatology, its remoteness from regions of industrial contamination, and the availability of weather data. Continuous recordings of surface potential gradient and both positive and negative conductivities were made.

The same data were used also by *Minton* [1955], who reported the use of the changes in conductivity and surface potential gradient as valuable aids to the operational forecasting of fog at Argentia. He formulated empirical rules and used them to forecast the onset, duration, and dissipation of fog from one to six hours in advance. Since banks of advection fog over the water surrounding Argentia advance and recede, and rise and lower over the airfield in an erratic manner, accurate short-term forecasting is both necessary and difficult.

Methods of measurement—The atmospheric conductivity is measured with a Gerdien-type cylindrical condenser mounted one meter above the ground. A voltage is applied to the outer electrode and the current to the central electrode is measured with a vibrating-reed electrometer. Air is drawn through the chamber with a velocity high enough that the change of current with applied voltage is linear and proportional to the conductivity. Both polar conductivities are recorded alternately from a single instrument by using a one-hour cycle timer which applies a constant positive voltage to the chamber for nearly half an hour, a negative voltage of equal amplitude for the next similar interval, and a zero-reference potential for a few minutes. The system is carefully calibrated and the overall accuracy is ±5 pct.

The surface potential gradient is measured with a grounded-rotor induction-type electric field meter, EFM, identical to that described by *Clark* [1957] for airborne use. Since the EFM is mounted one meter above the ground in a wooden box, the presence of the box augments the measured field as compared to that on a flat portion of the Earth's surface. This geometric augmentation factor was experimentally determined to be 2.15 by comparing the measured field at the box with simultaneously measured values from another EFM mounted flush with the Earth's surface. Hourly checks of the EFM zero and daily system-gain checks permit an overall accuracy of ±10 pct in the potential gradient measurement.

Sample records of potential gradient and conductivity are presented in Figure 1. The potential gradient $\partial V/\partial Z$ is related to the vertical (upward) electric field component E_z by the expression $\partial V/\partial Z = -E_z$ where both are in volts per meter. Since the fair-weather electric field is normally negative, the positive potential gradient is preferred for plotting. Total conductivity λ_T is the sum of the two polar conductivities. In the figure, the potential-gradient trace is concurrent with the conductivity trace immediately below it. The second conductivity trace is presented to illustrate the difference between a smooth, slowly changing trace and a 'jagged,' rapidly changing one. In subsequent figures the plotted values of the atmospheric-electric variables are hourly averages.

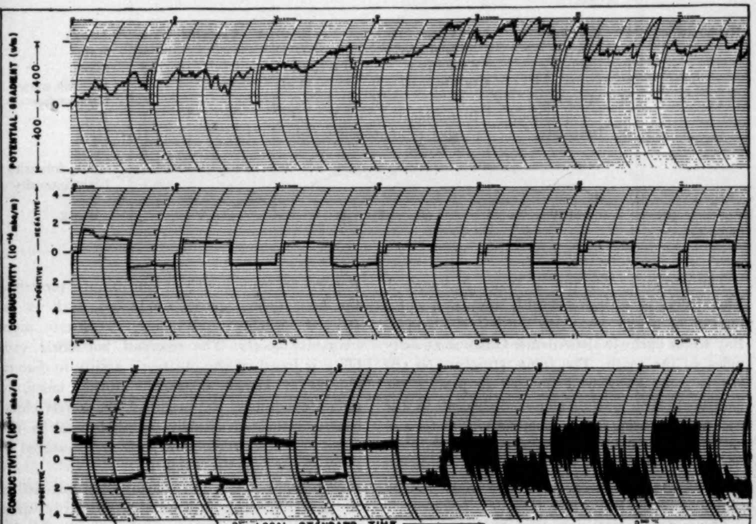

FIG. 1 – Records of potential gradient and conductivity

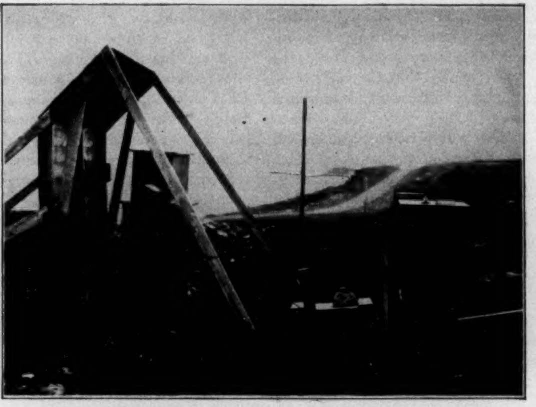

Fig. 2 – Station for atmospheric electricity

Table 1 – *Pertinent symbols from The Hourly Sequence Weather Reports*

Identification	Ceiling and cloud heights in hundreds of feet	Sky condition (Sky cover)	Visibility in statute miles	Weather and obstruction to vision
Explanation	V Variable A Aircraft B Balloon E Estimated M Measured P Precipitation W Indefinite	○ Clear (0.0) ⦶ Scattered (0.1 to 0.5) ⦷ Broken (0.6 to 0.9) ⊕ Overcast (1.0) In combination, symbols are reported in ascending order of height	V Variable	L Drizzle R Rain S Snow BS Blowing snow GF Ground fog F Fog H Haze K Smoke + Heavy intensity − Light intensity
Coded (example)	M3V	⦷ 7 ⊕	1½ V	L-FK

The station at Argentia is shown in Figure 2. The airfield is to the right with runways about a quarter of a mile away; to the left is Placentia Bay which opens to the Atlantic Ocean some forty miles to the south. The frame structure on the left is a sea-spray wall situated to protect the instrumentation during storms. Adjacent to the wall is the housing for the conductivity meter and recorders. The box on the right contains the electric field meter which measures surface potential gradient. An automatic calibration plate can be seen just to the left of the EFM.

The meteorological data used in this paper are taken from the *Hourly Sequence Weather Reports* prepared by the Argentia Fleet Weather Central which is located one-half mile east of the station. Reports are made hourly at four minutes preceding the hour unless special conditions, such as restricted visibility and ceiling, necessitate more frequent reports. The recorded horizontal visibility is based on the observer's ability to discern objects at known distances. During indefinite ceiling conditions, the height of the lowest cloud base is estimated visually. Symbols used in the *Hourly Sequence Weather Reports* are presented in abbreviated form in Table 1.

Data and results—The conventional forecasting of fog at Argentia is dependent primarily upon the analysis of the air-mass trajectory and the frontal positions. The cold Labrador current off the east coast and its component along the Grand Banks to the south in conjunction with the warm

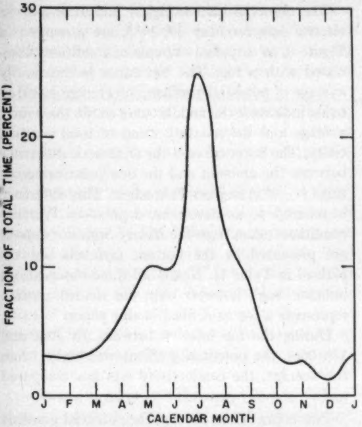

FIG. 3 – Yearly cycle of monthly averages of fog occurrence at Argentia, Newf. [Raymond, 1954]

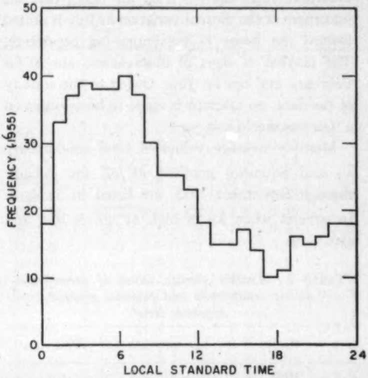

FIG. 4 – Variation in fog occurrence with time of day at Argentia, 1955

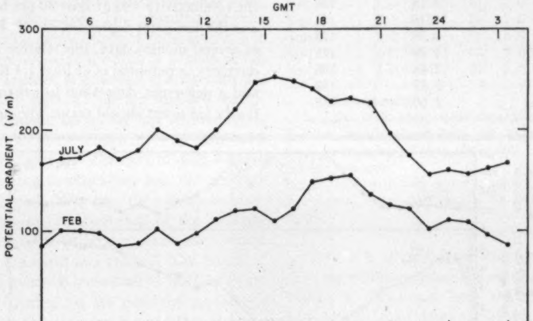

FIG. 5 – Comparison of diurnal variations of potential gradient for February and July, 1955 at Argentia

Gulf Stream provide an ideal fog-forming situation along the southern and eastern coast lines. In spring and early summer the differential heating rate between sea water and air causes a strong cooling in the lower layers of the air mass; consequently, fog forms frequently [*Taylor*, 1917]. In the fall and winter the reverse is true and fog is less frequent. The effect of this mechanism is illustrated by the data compiled by *Raymond* [1954] in Argentia and presented here as Figure 3. July is particularly noteworthy in that fog occurs 25 pct of the time.

The histogram of Figure 4 represents the number of times fog occurred in each hour interval of the day for 1955. Fog occurred most frequently in the early morning, local standard time, LST, 3½ hr behind GMT.

The diurnal variations of the potential gradient for February and July 1955 at Argentia are illustrated in Figure 5. The peaks of the two curves occur four hours apart; nevertheless there is general agreement with the universal diurnal variation. It is inferred from the figure that the maximum of the diurnal variation in July is shifted toward the hours of maximum fog occurrence. The number of days of observations are 20 for February and ten for July. Owing to the scarcity of the data, no attempt is made to be selective on a 'fair-weather' basis.

Monthly average values of total conductivity $\bar{\lambda}_T$ and potential gradient $\overline{\partial V/\partial Z}$ for January through September 1955, are listed in Table 2. In general when $\bar{\lambda}_T$ is high $\overline{\partial V/\partial Z}$ is low, and vice versa.

TABLE 2 – *Monthly average values of atmospheric-electric conductivity and potential gradient, Argentia, Newf.*

Month	$\bar{\lambda}_T$ (10^{-14} mho/m)	$\overline{\partial V/\partial Z}$ (v/m)
1955		
January	4.25	127
February	3.34	112
March	3.18	146
April	4.36	128
May	4.35	128
June	4.39	125
July	2.48	198
August	2.87	188
September	2.60	188

The observed meteorological and atmospheric-electric data for May 29, 1955, are presented in Figure 6, as a typical example of conditions associated with a fog. The top curve is the hourly average of potential gradient, its average for May being indicated; the middle curve shows the hourly average and the monthly mean of total conductivity. The lower curve is the arithmetic difference between the ambient and the dew-point temperatures $t - d$ in degrees Fahrenheit. This difference is referred to as dew-point depression. Weather conditions taken from the *Hourly Sequence Reports* are presented at the bottom (symbols are explained in Table 1). Nearly all these observations indicate 'fog'; however only the shaded portion represents a fog as defined in this paper.

During the fog interval between 7h 30m and 13h 06m, the potential gradient was higher than the average, the conductivity was low compared to $\bar{\lambda}_T$, and the dew-point depression was 0°.

Two hours before the fog, the potential gradient was variable about its monthly average, but increased prior to the fog onset. At the same time the conductivity was at least 30 pct below average and the dew-point depression was 1°. From analysis of several months data, this relative value of conductivity, a potential of at least 1.4 times average, and a dew-point depression less than 2°, indicate that a fog event should occur. The lowering trend

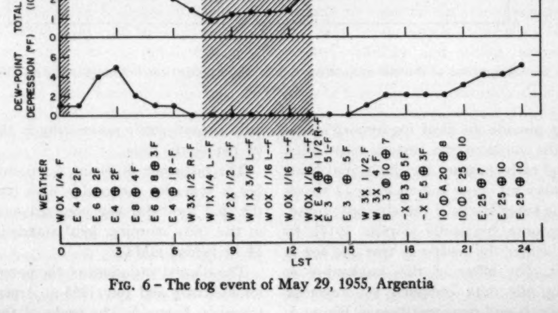

FIG. 6 – The fog event of May 29, 1955, Argentia

in the dew-point depression indicates an increase in water content, which is necessary but not sufficient for fog formation. This is borne out by the fact that frequently the dew-point depression is less than 2° in the absence of fog.

During the fog event, one hour before dissipation, conductivity started increasing, indicating dissipation even though the dew-point depression remained at 0°.

A summary of the statistical analysis of short-term (<5 hr) fog events is presented in the upper part of Table 3. The following conclusions are evident. In fog, the average conductivity level $\bar{\lambda}_f$ is generally less than 65 pct of the monthly mean, and the dew-point depression is always less than 2° and is generally 0°. The indications of the onset of fog, that is conductivity decreasing by at least 30 pct of $\bar{\lambda}_T$ accompanied by the dew-point depression approaching zero, occur from a half to two hours in advance. The indication of dissipation, conductivity increasing toward the average, occurs in most of the events at least one hour in advance despite the frequent absence of any rise in the dew-point depression above zero even after the fog has dissipated. The potential-gradient data are missing during many of these events, but when data are available the ratio of average in fog to monthly average is generally greater than 2.0 (approximately full-scale on the recorded trace).

Fogs at Argentia frequently last for five hours or more. These extensive fogs are very dense and generally homogeneous. The data of July 3–4 are typical of a long homogeneous fog and are presented in Figure 7. Note that the average conductivity level in fog is about half of the monthly mean and that the variations about the average level in fog are slight and gradual. The summary of long-term events is presented in the lower part of Table 3. During fog the potential gradient is almost always at least twice the monthly average; prior to onset, the potential gradient starts rising above average, and approaches the average before dissipation. A comparison of the two parts of Table 3 shows the similarity of the average levels of atmospheric-electric quantities in both long and short fog events. The table summarizes all the available atmospheric-electric data pertaining to fog for the ten months covered by this investigation.

TABLE 3 – *Summary of fog events in Newfoundland*

Date	Advance indication of onset	In Fog				
		Duration[a]	Dewpoint depression	Advance indication of dissipation	$\bar{\lambda}_f/\bar{\lambda}_T$	$\overline{(\partial e/\partial z)_f}/\overline{(\partial e/\partial z)_T}$
1955	hr	hr	°F	hr		
Jan. 6	1.2	1.6	≤2	1.0	0.62	...
Jan. 16	0.7	1.5	0	1.2	0.57	...
Feb. 11	1.5	3.8	0	1.0	0.28	...
Feb. 13	1.0	1.9	0	0.8	0.74	...
Mar. 2	0.5	1.0	0	0.5	0.62	1.2
Mar. 10	1.0	3.0	≤2	1.0	0.29	...
Mar. 25	0.5	1.5	0	1.0	0.36	>2.0
May 28	0.0	3.0	≤2	0.0	0.60	>2.0
July 19	...	3.0	≤2	1.5	0.43	...
July 25	1.5	4.5	0	...	...	>2.0
Sept. 16	2.0	2.0	0	0.0	0.75	>2.0
Feb. 23	1.5	11.0	0	1.5	0.48	>2.0
Feb. 24	0.0	5.7	0	1.0	0.57	1.6
Mar. 12	1.5	7.0	0	2.5	0.28	...
May 29	1.5	5.7	0	1.2	0.27	>2.0
June 4	0.7	5.0	≤2	1.1	0.65	>2.0
July 4	1.0	8.0	≤2	1.5	0.52	1.4
July 24	1.0	24.0	0	2.0	...	>2.0
Sept. 2	2.5	10.0	0	1.0	0.42	1.5
Sept. 4	0.0	19.4	0	2.0	0.33	>2.0
Sept. 5	1.0	10.0	0	0.0	0.31	>2.0
Sept. 28	3.0	5.0	0	0.0	0.74	>2.0

..., data missing.

In July 1955, there were an additional 167 hr of fog for which there were no atmospheric-electric data; meteorological data show that there was fog 27 pct of the time.

[a] Divided into two groups; upper part, less than five hours; lower part, equal to or more than five hours.

Occasionally in long-term fogs small openings, or 'holes,' occur for intervals ranging from fifteen minutes to one hour. During these periods, aircraft are permitted to land and take off; consequently, it is advantageous to forecast whether or not a fog will have holes. The event of February 23, Figure 8, illustrates how inhomogeneous fogs (those with holes) differ electrically from homogeneous fogs (Fig. 7). The average level of conductivity during the February 23 event was about half of the monthly mean; however, large and abrupt variations about $\bar{\lambda}_f$ occurred. This is in contrast to the smooth and gradual changes shown in Figure 7. An examination of the conductivity records of the two events shows a difference in the fine structures; the trace of July 4 is smooth and slowly changing, while the trace of February 23 is jagged and changing rapidly from minute to minute as shown in the bottom trace of Figure 1. These variations are masked on the later figures by hourly averages.

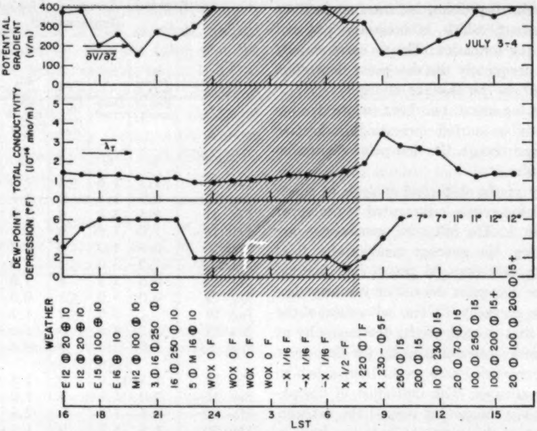

FIG. 7 – Example of homogeneous long-term fog event July 3–4, 1955, Argentia

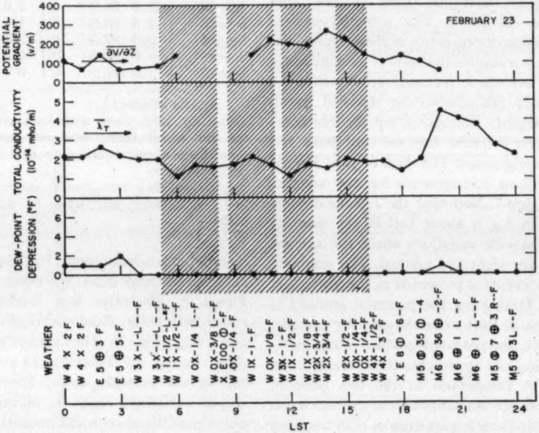

FIG. 8 – Example of inhomogeneous long-term fog event February 23, 1955, Argentia

The meteorological data for February 23 reveal that holes appeared in the fog at approximately 08h 30m, 11h 30m, and 14h. A rather abrupt rise of some 30 pct in λ_t occurred one to two hours prior to each of these holes. The potential-gradient data for such fogs are too sparse for analysis, but observers in the field have indicated that the behavior of potential gradient assists in determining if the conductivity increase (or fluctuation) is to be used for forecasting a hole or dissipation.

Discussion—Within the limits of our definition of the presence of fog, that is, ceiling below 200 ft and horizontal visibility less than a half mile, the presented data show a high degree of correlation between the atmospheric-electric measurements and the occurrence of fog. During such fog the values of dew-point depression, potential gradient, and conductivity are found to lie within certain limits. The high level of positive correlation shown in Table 4 illustrates the validity with which the limits can be chosen on the basis of a statistical study such as this one.

The technique of using atmospheric-electric variables to forecast fog depends on trends in the variables prior to reaching the limits chosen. Normalized to the monthly average, values of the variables for fog events from January through September, presented in Figure 9, show trends before onset and before dissipation. As previously stated, the potential gradient data are missing for many of the short events; therefore a normalized curve of the gradient for such events would be inconclusive. Between two and three hours before onset, the dew-point depression is within 2°F and decreasing; the potential gradient is increasing and reaches a relative value of 1.4 at -2 hours; the conductivity is decreasing and reaches 0.70 at -1 hour for short events and -3 hours for long events. These relative values of potential gradient and conductivity do not normally occur in fair weather, hence are noteworthy. The dew-point depression remains below 2° until sometime after dissipation while the potential gradient shows a lowering trend and the conductivity a rising trend for an hour before dissipation. On the 'wind rose' the point from which the direction lines originate in each case is the average wind speed in knots, and the lengths of the direction lines are proportional to the number of observations of specific wind directions. The average wind speed and direction are presented to show that such data are inconclusive for purposes of short-term fog forecasting.

Suggested mechanisms—Atmospheric conductivity is due primarily to singly charged small ions of relatively high mobility in the size range 10^{-7} cm and less, where

$$\lambda = nek$$

Here n is the small-ion density, e the elementary charge, and k the mobility. The conductivity reduction in fog is due to a decrease in small-ion density caused by the loss of small ions by diffusion to capturing fog droplets. This, however, does not explain the lowering of conductivity which has been observed prior to fog. Other, smaller

TABLE 4 – *Correlation between limiting conditions of atmospheric-electric variables and fog*

Conditions	Fog intervals[a] considered	Intervals when conditions are met	Pct of positive correlation
$(t - d) = 0°F$	354	311	88
$\bar{\lambda}_f/\bar{\lambda}_T < 0.65$	218	200	92
$(\overline{\partial V_f/\partial Z})/(\overline{\partial V/\partial Z}) > 2.0$	210	182	87

[a] Half-hour intervals.

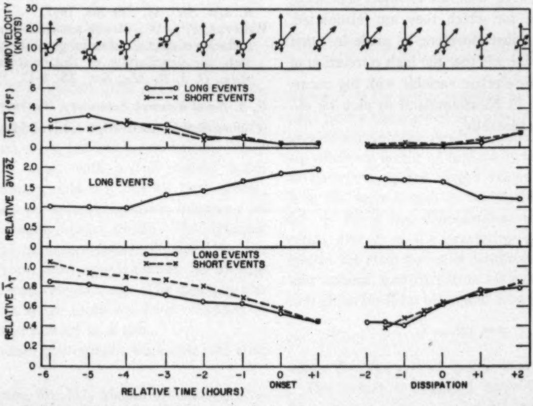

FIG. 9 – Normalized values of atmospheric-electric and pertinent meteorological variables

particles which are known to play a role similar to that of fog droplets in reducing λ include Aitken particles (10^{-7} to 10^{-5} cm) and haze particles (10^{-5} to 10^{-4} cm). Since the largest particles are activated first, the Aitken particles do not normally constitute the active fog condensation centers and are too small to produce appreciable scattering of visible light according to the Mie theory. However, the larger haze particles participate in both processes, according to *Junge* [1958]. Thus, the observed conductivity decrease prior to fog can be attributed to an increase in the density of the Aitken particles or an increase in the size of the larger particles.

The density increase could be explained by advection of air in which the aerosol density and size are changing with horizontal position, while the size increase could be due to cooling of the air *in situ* causing condensation. Such cooling could also take place during advection, thus creating the required aerosol size distribution with distance. It is recognized that the activation of Aitken particles as condensation centers implies an initial absence of haze and larger particles, perhaps due to the remoteness of the site from industrial pollution sources, or more probably to a prior precipitation of these particles in the sustained high relative humidity environment.

Summary—The trends of atmospheric-electric variables may be used to assist conventional meteorological methods in forecasting fog more accurately at Argentia. The quantitative limits placed upon these variables are certainly dependent upon the locale for which they are formulated. Similar studies must therefore be made in other areas to determine whether the high correlation of each atmospheric-electric variable with fog occurrence is unique in Newfoundland or may be encountered more generally.

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Rainfall Measurement by Radar Using Photographic Integration Techniques*

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Abstract—Methods have been devised to estimate areal rainfall amounts as portrayed by radar. This is accomplished by a continuous photographic integration of the plan position indicator (PPI) scope over periods of one or more hours giving the hydrologist almost immediate information on the precipitation falling on an area of over 30,000 sq mi. These investigations have developed echo-density contour maps which correlate favorably with isohyetal maps. The limitations and capabilities of present radar systems for purposes of radar integration of rainfall also have been evaluated.

Introduction—The use of radar as a meteorological tool for determining precipitation patterns qualitatively in recent years has led to many attempts to also determine the quantity of precipitation over the area of radar coverage. Investigations have been made by the Massachusetts Institute of Technology, Canadian Army Operational Research Group, Thunderstorm Project, Illinois State Water Survey, McGill University, University of Florida, Texas A & M College, and others. The first known use of photographic integration of rain echoes on radar, which is the basic method used in the research reported here, was made by *Rockney* [1954]. All such investigations were immediately faced with many serious problems both in obtaining the radar precipitation data and in providing reasonably accurate rainfall sampling for correlation purposes over the area of radar coverage. Only a few of these problems have been solved in the present study, but the techniques used have led to tentative solutions to other, especially equipment, problems and increased optimism for rainfall measurement by radar [*Hiser* and *Conover*, 1956] [*Hiser* and others, 1957].

Equipment used—Most of the data for this study were obtained on a 10.7-cm wave length, Navy model SP-1M radar with a 3.2° conical beam (antenna diameter 2.44 m), 750 kw peak power, and 635 pulses per second repetition frequency on its one microsecond pulse length. The dynamic range and the minimum detectable signal for the receiving system were approximately 32 db and 4.0×10^{-13} watts respectively. The antenna was located 135 ft above mean sea level, elevated to +0.5° tilt, and rotated at 3 rpm.

The integrated photographs were obtained with two 8 × 10-inch plate back cameras mounted on Navy model VD-2, seven-inch PPI repeater scopes. The use of two integrator cameras permitted simultaneous comparisons of different photographic materials, repeater operation techniques, and camera aperture settings. The camera shutters were left open continuously for the entire period of integration which ranged from one to six hours. All gain and intensity settings were calibrated and recorded so that optimum conditions could be reproduced as accurately as possible from day to day. Processing of the 8 × 10-inch papers and films was also carefully controlled so that a constant gamma was obtained for each photographic material.

Theoretical considerations—Theoretical 'Minimum detectable rainfall rates' and 'receiver saturation rainfall rates' for the SP-1M, Table 1, were computed by the use of the above radar parameters and the equation of *Marshall* and others [1947].

$$P_r = P_t \frac{\pi^4 A h}{8 r^2 \lambda^4} \frac{(n^2 - 1)^2}{(n^2 + 1)^2} Z \tag{1}$$

where P_r is the power received in watts; P_t is the peak power transmitted in watts; A is the effective area of the antenna in square meters, based upon an efficiency factor of 0.55; h is the pulse length in meters; r is the target range in kilometers; λ is the wave length in centimeters; $(n^2 - 1)^2/(n^2 + 1)^2$ is the dimensionless refractive index term; and Z is the scattering quantity which relates the sixth power of raindrop diameters in a unit volume, mm^6/m^3, to rainfall rates. The equation given for Z by *Gunn* and *East* [1954] was used

$$Z = 353\, R^{1.52} \tag{2}$$

where R is the rainfall rate in mm/hour.

The values in Table 1 have been converted from metric units given by (1), to nautical miles

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TABLE 1 – *Theoretical minimum detectable and receiver saturation rainfall rates for SP-1M radar on one microsecond pulse*

Range from radar	Min. detectable rainfall rate	Receiver saturation rainfall rate
naut mi	inch/hr	inch/hr
10	....	0.18
20	....	0.43
30	....	0.74
40	0.01	1.05
50	0.01	1.40
60	0.02	1.80
70	0.02	2.02
80	0.02	2.60
90	0.03	3.10
100	0.03	3.50

and inches per hour. These minimum detectable rates and saturation rates are based upon the assumption that the precipitation target completely fills the radar beam in the plane normal to the axis along which the beam is directed and to a depth of at least one-half pulse length in range. It is believed that the actual receiver saturation rainfall rates and the minimum detectable rates for the SP-1M radar used in this research were close to these calculated values.

Methods of analysis—The densities of echoes were read on a Welch Densichron transmission-type densitometer which was calibrated in accordance with standards of the American Standards Association (ASA). Density (or opacity) was then compared with the actual rainfall recorded by raingages during the period of integration. In this research, each integration or a series of integrations is treated as an entity in order to eliminate the effects of day to day variations in the radar and photographic processes.

The 'point' method, in which the rainfall amounts were correlated with the film's echo density measured directly over the raingage location, was used extensively. Densities were read using overlays which contained the positions of 71 recording raingages within 100 naut mi of the radar. This method suffers from the inability to determine the raingage locations accurately on the integration film, because of certain non-linearities and day to day variations in the scale of the radarscope, as well as serious difficulties in accurately computing precipitation-time relationships. Both are extremely critical requirements because of the high rainfall (and therefore density) gradients produced by the showery precipitation typical of the experimentation area.

An 'areal' method was developed in which rainfall amounts are used to produce an isohyetal map and densities are read from the film onto a grid system to form a density contour map which is compared with the isohyetal map. This method smooths out errors that are inherent in the point method, since large numbers of density readings are used to produce the contours. The grid system is also easily adaptable to fast and accurate data transmission by teletype or facsimile under operational conditions.

Figure 1 shows one of the integrations with a map of Florida superimposed. This photograph was made on Fine Grain Positive film during the three hour-period 14h 00m – 17h 00m EST, February 26, 1957. Figure 2 is an enlarged echo-density contour map which illustrates the areal method of analysis. It was constructed by reading echo densities within the rectangle shown to the north of the radar station in Figure 1. Density readings were taken in each of the grid squares where an echo was present. The echo contours are labeled in ASA density. Rainfall totals for the three-hour period of integration are plotted at the gage locations, solid dots, and 'NR' indicates no record.

Problems involved—The density of an echo over a raingage at a particular range is not only a function of the rainfall rate and duration but also of the following parameters:

(a) Radar: Wave length, power transmitted, pulse length, antenna gain, normal range attenuation of radar signals, minimum detectable signal, dynamic range of the receiver, antenna rotation speed, and pulse repetition frequency.

(b) Precipitation: Size, shape, composition, and motion of particles; height of detectable cloud; and other factors such as vertical wind shear and humidity differences between echo level and ground.

(c) PPI scope: Age and other characteristics of the cathode ray tube (CRT) and other components, dynamic range of the video amplifier for the scope, intensity settings, focus, range increments used, and writing speed of the sweep.

(d) Photographic: Aperture of camera iris, length of exposure, characteristics of the light sensitive material used, and processing techniques.

It appears obvious that direct correlations between echo densities and rainfall amounts which are obtained over a period of time for a given radar are applicable only to that radar, and even then are subject to some change as radar and repeater systems age and change or are modified. Results obtained with the SP-1M radar under varying

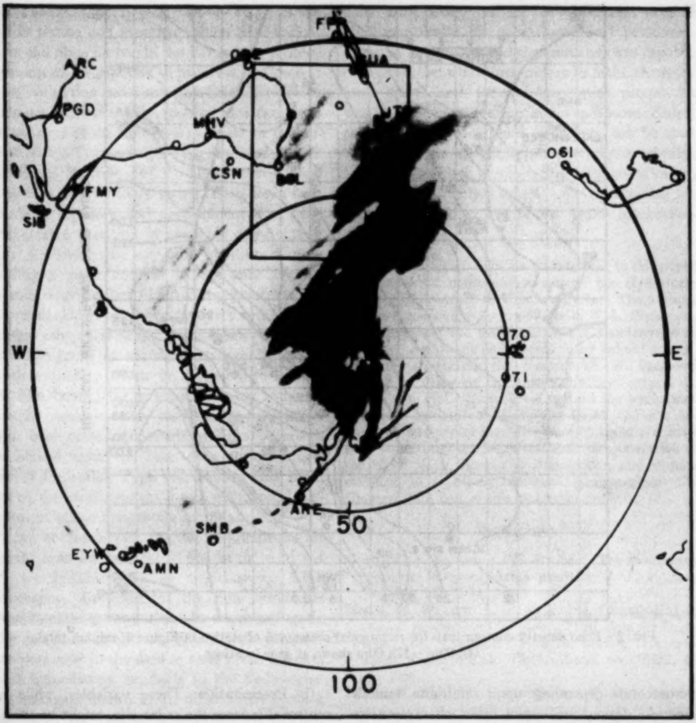


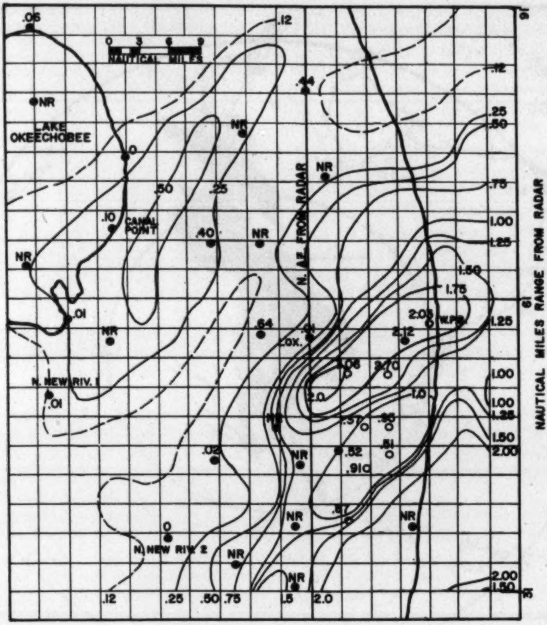
FIG. 1 - Photo-integration 365A, 14h 00m - 17h 00m EST, Feb. 26, 1957, with map of southern Florida superimposed

meteorological conditions and carefully controlled research procedures indicate that a definite relationship can be established between echo density and total rainfall for a given radar. However, they also revealed a number of radar and other parameters which should be optimized for purposes of rainfall integration as well as for the advancement of radar as a general meteorological tool.

The receiver saturation rainfall rates for the SP-1M and most other radars are a serious handicap to photographic integration. When these limiting rainfall rates are exceeded there is no way to ascertain the true intensity of the rainfall. Because the receiver saturation rainfall rate increases with range from the radar (Table 1), the most reliable radar-rainfall correlations obtained by this project are those beyond 40 or 50 miles range where the saturation problem is less important.

Procedures and equipment recommended for optimum results in integrating rainfall by radar—The following five conditions should be attained.

(a) Radar: The wave length must be short enough to detect most precipitation out to near 100 mi and to provide economy of power and antenna size characteristics; but it must be long enough so that there is no appreciable precipitation attenuation. At present a wave length near 10 cm appears best. The pulse length should be short enough to provide good echo resolution and long enough to provide enough power for desired minimum detectability of light rain: one to four


.06
.12
0 3 6 9
NAUTICAL MILES
.44
NR
LAKE OKEECHOBEE
0
.50
.25
.10
CANAL POINT
.40
NR
.01
N. NEW RIV. 1
.01
.64
.01
COX.
N. AZ. FROM RADAR
.12
.25
.50
.75
1.00
1.25
1.50
1.75
2.03
W.P.B.
2.12
1.25
2.06
2.70
2.0
1.0
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1.25
1.50
2.00
.37
.36
.51
.52
.91
1.5
.02
.57
0
N. NEW RIV. 2
2.00
1.50
.12
.25
.50
.75
1.5
2.0
91
61
NAUTICAL MILES RANGE FROM RADAR

FIG. 2 – Echo density contour map for rectangular area north of station in Figure 1, rainfall totals 14h 00m – 17h 00m shown at gage locations

microseconds depending upon minimum rainfall detection desired and upon other characteristics of the radar.

Receiver and display characteristics should be such that a dynamic range on the order of 60 to 80 db is available to portray precipitation rates from a few hundredths of an inch per hour at ranges in excess of 100 mi to over ten inches per hour at a range of ten miles without overloading or saturating. Such a receiver should have a logarithmic output in order to prevent saturation of the cathode-ray tubes and other indicator components. It should also incorporate exponential range and sweep writing speed correction circuitry to permit echoes representing equal rainfall intensity to be portrayed at equal intensity on the face of the CRT regardless of their ranges. Both the receiver with a large dynamic range and the range correction device are under development at the University of Miami.

(b) Precipitation: These variables, while not controllable from the radar site, might be studied more effectively and identified more readily by use of improved radars having the optimum characteristics mentioned above.

(c) PPI scope: The aging of the CRT and other components cannot be rigidly controlled, but good resolution is an absolute necessity. A seven-inch CRT or larger is required to give proper detail, and range increments should be such that only 15 to 100 mi range is portrayed, with the bloom at the center of the scope caused by ground clutter removed by a short range STC or other suitable suppression circuits. The antenna should scan at constant speed of from two to four revolutions per minute since rotation speed determines the number of times a target is illuminated during a given time interval and this affects the echo density on the film. Calibrated dials are necessary on all equipment.

(d) Photographic: A good part of two years was spent in testing and experimentation with various papers and films for use in the integration process. Films proved far superior to papers tested both in ease of evaluation and dimensional stability during processing, minimizing the problem of fitting them with overlays of the rain-gage network for evaluation. Kodak's Transmission Type A (Tran. A) and Fine Grain Positive (FGP) films proved more useful than many others tested. Both have wide latitude of exposure and development, but FGP has a greater variation in available density than Tran. A. Under the exposure conditions used, including a radar receiver having only average dynamic range, either film accomplished the desired result. However, when receivers with greater dynamic range and scopes capable of portraying this entire range as variations in light intensity become available, it may be necessary to use the FGP film having the greatest possible range of available densities for recording precipitation echoes over extended periods of time. Although only limited work has been done with the new Polaroid Projection Type 46L film, it may fulfill most of the requirements for an economical and convenient photo integration material.

It can be shown that the film requirements for constant exposure integration are far more critical than for instantaneous or single sweep CRT photography. In addition, the film should be orthochromatic so that it can be developed easily under safe-light conditions by relatively inexperienced personnel in the field so as to make the data almost immediately available to the hydrologist.

(e) Raingage network: In order to calibrate a given radar for rainfall integration, an efficient raingage network composed of accurate and well-tended gages is necessary. In order to make the best use of a limited number of gages, it is logical that these should be placed in the quadrant which is most vulnerable to destructive floods. Placing them in this fashion will increase the chances of obtaining one or more key gage records to use in evaluating the radarscope photo integration of a flood potential rain.

Conclusions—Although this problem has been studied using an inadequate, but above average, radar, methods have been devised which can be used with other radars to integrate rainfall photographically by operational field personnel. Many of the present radar parameters are capable of improvement in future radars to make them far more useful both for the integration process as well as for general meteorological purposes. Either the point or areal method of analysis can be used to establish the relationship between recorded rainfall and integrated precipitation for a given radar, but the areal method appears more promising for general operational use of the photo integration process.

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The Growth of the Atmospheric Internal Boundary Layer

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Abstract—When air, whose wind profile is in equilibrium with an underlying surface, passes to another surface with different roughness, a layer is formed in which the air has adjusted to the new surface. Generally this layer will grow in depth downwind. Assuming the logarithmic wind-speed distribution and Karman's integral equation the height of this layer is computed theoretically as a function of distance. A dimensional argument is also presented which qualitatively confirms the result that the boundary layer grows as the $\frac{4}{5}$ power of the distance downwind and is independent of wind speed. The effect of thermal stability is estimated and found to be relatively small, raising the height of the layer in lapse conditions and lowering it in inversions. Some data are discussed which qualitatively confirm those results but which cannot be considered to be conclusive.

Introduction—In the study of fluid flows a boundary layer is the region in which the effects of the boundaries on the flow are felt. The effect of the boundary is exhibited in a number of ways, the usual ones discussed being transitions from straight flow with no velocity shear to laminar flow or turbulent flow with their respective shears. In this work we shall concern ourselves with the transition from one state of fully developed turbulent flow to another state.

Fully developed turbulence in the region of a rough surface exhibits certain statistical properties which depend, among other things, upon surface roughness and thermal properties. In general, if wind has been blowing steadily over a region of statistically homogeneous roughness for some time, the profile of mean velocity will be in equilibrium with the underlying surface. Assuming the upper-level wind does not change with distance or time, the profile will be the same over the whole area. If, however, this air should pass over another area of different surface roughness or different thermal properties a new equilibrium profile will result. It is reasonable to assume (and in fact observable) that the flow does not immediately adjust at all levels to this new surface but rather the adjustment takes place gradually, the depth of the new equilibrium layer increasing with distance downwind from point of discontinuity in roughness. The transition from the original wind profile will be assumed to take place in a zone of very small vertical extent. This zone will actually be considered as a surface dividing the lower atmosphere into two distinct layers.

The lower layer will be called the internal boundary layer, and the computation of the height of this layer, as a function of distance from the point of transition, is the problem undertaken here.

List of symbols—The following symbols are used.

a	coefficient in power-law formula for boundary layer
a_*	virtual coefficient in power-law formula for boundary layer
c	square root of m
h	height of boundary layer
k	Karman's constant
m	ratio of z_0 below boundary layer to z_0 outside boundary layer
n	exponent in power-law formula for boundary layer
Ri	Richardson number
S	non-dimensional stability factor
u	mean wind speed in x direction
u_h	mean wind speed at top of boundary layer
u_*	friction velocity
x	horizontal coordinate, positive downwind
X	x/z_0
z	vertical coordinate, positive upward from surface
z_0	roughness parameter
$z_0{}^*$	virtual roughness parameter
Z	z/z_0
Z_1	h/z_0
ν	kinematic viscosity
ρ	air density
τ_h	shear stress at height h
τ_0	shear stress at surface

primed quantities refer to values outside boundary layer umprimed quantities to values in boundary layer or general case.

Modified Karman integral theorem—In order to arrive at an analytic expression for the height of the internal boundary layer, we will first make use of a slightly modified form of the Karman integral equation [*Lamb*, 1932, pp. 685–686]. Karman then shows that the total horizontal flux of momentum out of a region bounded by the top of the boundary layer, the surface and two vertical lines a distance δx apart is

Loss of momentum
by advection

$$= \left\{ d/dx \int_{z_0}^{h} \rho u^2 \, dz - u_h \, d/dx \int_{z_0}^{h} \rho u \, dz \right\} \delta x$$

Assuming conservation of momentum (steady state and no body forces) in the boundary layer, this expression must also equal the net gain of momentum due to vertical flux into the region. The gain by vertical momentum flux is simply the difference in the shearing stress between the top and bottom of the column of air considered. Thus

$$\frac{d}{dx} \int_{z_0}^{h} \qquad - u_h \frac{d}{dx} \int_{z_0}^{h} \rho u \, dz = \tau_h - \tau_0 \qquad (1)$$

Both stresses are positive if in the direction of x. In order to use this relation for the evaluation of h, an expression for the variation of u with height must first be chosen.

In order to approximate most closely the actual atmospheric conditions usually observed we will make use of the logarithmic wind profile

$$u = u_*/k \ln z/z_0 \qquad (2)$$

In this relation k is assumed equal to 0.4; u_* is defined as

$$u_* = (\tau_0/\rho)^{1/2} \qquad (3)$$

Changes in z_0 will be assumed to represent changes in surface characteristics in this study. Strictly speaking (2) is applicable only in adiabatic conditions and an attempt to correct the final results for nonadiabatic conditions will be made later.

Internal boundary layer for adiabatic conditions—Figure 1 is a schematic diagram of the internal boundary layer. Assume that the following equations describe the flow

$$u' = u_*'/k \ln z/z_0' \qquad (4)$$

$$u = u_*/k \ln z/z_0 \qquad (5)$$

where the primed quantities in (4) refer to the conditions upwind from the edge and outside the boundary, and (5) describes the flow in the boundary layer. The quantity u_* is assumed to be a function of x but not of z. This is tantamount to saying that the stress in the boundary layer changes with x but at any location it is constant throughout the layer up to $z = h$.

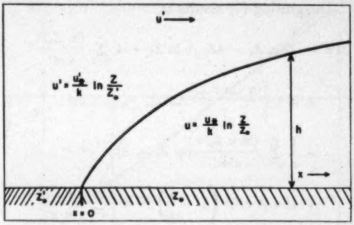

FIG. 1 – Schematic diagram of internal boundary layer

Also assume that at $z = h$, $u' = u_h$. This insures continuity of wind at the top of the boundary layer but further implies a discontinuity in stress. This latter assumption is of course physically unrealistic but comes from the assumption that the change from one regime to another takes place abruptly. In reality, there is probably a transition zone where neither (4) nor (5) is an accurate description of the flow. However, if the transition zone is narrow enough, this need not be considered. Observations seem to support the reasonableness of this assumption.

The assumption of constant stress in the two regions implies that the flux of momentum into the boundary layer from above is $\rho u_*'^2$ and the amount subtracted at the ground is ρu_*^2. Hence (1) can be written

$$\frac{d}{dx} \int_{z_0}^{h} u^2 \, dz - u_h \frac{d}{dx} \int_{z_0}^{h} u \, dz = u_*'^2 - u_*^2 \qquad (6)$$

provided there is no pressure gradient in the x direction.

The solution of (6) will be only indicated here; the full development is given by *Elliott* [1958].

Making these changes in notation $Z = z/z_0$, $Z' = z/z_0'$, $Z_1 = h/z_0$, $X = x/z_0$, and $m = z_0/z_0'$, substituting from (4) and (5), and making use of the assumed continuity of velocity at $z = h$, we arrive at the following differential equation

$$\left\{ \ln Z_1 - 3 - \frac{1}{Z_1} + \frac{4}{\ln Z_1}\left(1 - \frac{1}{Z_1}\right) \right\} \frac{dZ_1}{dx} = \left(1 + \frac{\ln Z_1}{\ln mZ_1}\right) \frac{k^2}{z_0} \qquad (7)$$

Integrating (7) results in

$$\begin{aligned} 2kX = {} & Z_1 \ln Z_1 - 4Z_1 - \ln Z_1 + 4 \sum_{n=1}^{\infty} \frac{(\ln Z_1)^n}{n \cdot n!} \\ & + \ln c \left\{ \frac{\ln (\ln c\, Z_1)}{c} (\ln Z_1 - 3 - 2c) \right. \\ & \left. + \frac{1}{c} \sum_{n=1}^{\infty} \frac{(\ln c\, Z_1)^n}{n \cdot n!} (\ln Z_1 - 3) \right\} \\ & + 4(\ln \ln cZ_1) \left(1 - \frac{1}{c}\right) + 4 \left\{ \sum_{n=1}^{\infty} \frac{(\ln Z_1)^n}{n \cdot n!} \right. \\ & \left. - \frac{1}{c} \sum_{n=1}^{\infty} \frac{(\ln c\, Z_1)^n}{n \cdot n!} \right\} + \text{constant} \end{aligned} \quad (8)$$

where the constant of integration will depend upon values of c as determined by the condition that $h = z_0$ at $x = 0$.

The boundary conditions present certain difficulties. The most convenient assumption to be made, that the boundary layer begins to grow at $x = 0$, may not be true in actual practice. Also, near the origin where the boundary has not attained an appreciable height, the assumptions of constant stress and the logarithmic profile may not be strictly accurate. Consequently, not much reliance should be placed on the solutions in the very lowest layers (say $z = 10$ cm, $x = 100$ cm).

Eq. (8) gives X explicitly as a function of Z_1 with m as a parameter, or Z_1 implicitly as a function of X and m. Sufficient numerical work was carried out to define the curves for Z_1 versus X over a wide range of these variables for the following values of m: 0.01, 0.05, 0.1, 0.2, and 0.5($z_0 < z_0'$); 1 (no change of surface condition); and 2, 5, 10, 50, 100 ($z_0 > z_0'$). Figure 2 shows the plots of three of the curves which were obtained from the computations.

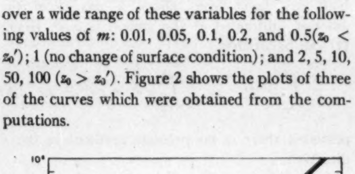

FIG. 2 – Growth of internal boundary layer with distance

The formal solution is extremely clumsy, and the general shape of the family of curves for m in the Z_1X plane is not apparent from the equation itself. Actually, it was somewhat surprising when the graphs of (8) showed such a smooth appearance. It is apparent from the curves in Figure 2 that the functional relationship can be approximated by the simple formula

$$Z_1 = aX^n \quad (9)$$

for $X > 10^3$. The latter condition implies that x should be of the order of ten meters or greater for typical ground surfaces. The slope of the straight portion of the curves in Figure 2 leads to a value for m of 0.80; the corresponding value for a is 0.75 for the case of $m = 1$. It was found that the value of n could be taken constant regardless of m, and for the range of m considered the coefficient a varies from 0.6 to 0.9 approximately according to the relation

$$a = 0.75 - 0.03 \ln m \quad (10)$$

It is seen from this result that the height of the boundary layer (for a given position x) will be greater for air flowing from a rough surface to a surface of less roughness ($z_0 < z_0'$) than for the opposite situation. However, even if z_0 differs by a factor of 100 from z_0', the height is changed by only 20 pct relative to the case of $m = 1$. Comparison of the above results with observations is presented in a later section.

Dimensional argument—A result of the previous section which was not intuitively obvious was that (8) does not contain the wind speed or u_*. In other studies of boundary layers the height is dependent upon some power of the wind speed or free stream velocity. In the transition from straight to laminar flow over a smooth plate the height is proportional to the square root of the free stream velocity and for laminar to turbulent flow the height is proportional to the one-fifth power of the free stream velocity [see *Schlichting*, 1955].

The turbulent flow discussed here is physically distinct from the case we have been considering in the previous section. In the case of turbulent flow over a hydrodynamically smooth surface viscosity is an influencing factor, whereas, in the case under consideration, flow over a hydrodynamically rough surface, the surface characteristics play a more dominant role than viscosity. In the case of a smooth surface, a thin laminar sublayer occurs close to the surface while for a rough surface the turbulence extends to the surface. In fact, in the case of a smooth surface, previous investigations [*Schlichting*, 1955] indicate

$$u_h h/\nu \propto u_h x^{0.8}/\nu \tag{11}$$

Experimental evidence also indicates that the velocity profile

$$u/u_* \propto \ln (u_* z/\nu) \tag{12}$$

in the case of turbulent flow over a smooth plate and

$$u/u_* \propto \ln z/z_0 \tag{13}$$

in the case of turbulent flow over a rough plate. In the latter case viscosity is no longer important, and z_0, a measure of the surface characteristics, appears. Furthermore it appears that the term $u_* z_0$ has replaced ν in (12) as the relevant parameter for determining the velocity profile. If it is permissible to extend these empirical results for the profile to the boundary layer situation then the replacement of ν by $u_* z_0$ in (11) leads to

$$(u_h/u_*)(h/z_0) \propto (u_h/u_*)^{4/5} X^{0.8} \tag{14}$$

However

$$u_h/u_* \propto \ln h/z_0 \tag{15}$$

by (13). So finally we have, substituting (15) in (14),

$$(h/z_0)(\ln h/z_0)^{1/5} \propto X^{0.8} \tag{16}$$

Thus this argument has resulted in the elimination of the wind speed and u_* as well as the viscosity, which is in agreement with our previous results.

The term $(\ln h/z_0)^{0.2}$ which appears in (16) is virtually constant over a large range of h/z_0, varying from 1.47 at $h/z_0 = 10^3$ to 1.79 at $h/z_0 = 10^8$. Consequently (16) will not be radically different from the approximate form (9). Figure 3 shows a comparison of (8) for $m = 1$, (9) with $a = 0.75$ and $n = 0.8$, and (16) fitted to (8) at $h/z_0 = 10^3$. One can see that (16) can be made a better approximation to (8) than (9).

Effect of stability—It now remains to estimate the effect which atmospheric stability might have on the height of the internal boundary layer. Ideally we would like to be able to substitute some form for the nonadiabatic profile in (1) and integrate as was done with the adiabatic profile (2). However, the equations available to describe the non-adiabatic profile all proved intractable. Consequently, a method by which the effect of stability could be estimated was devised. This method is not accurate but it serves to indicate the general effect.

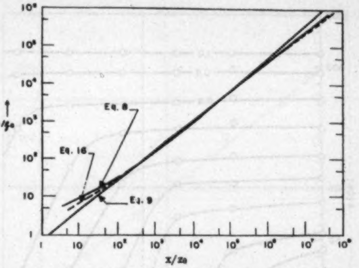

FIG. 3 – Comparison of Equations (8), (9), and (16)

In a review of some of the descriptions of non-adiabatic profiles, *Elliott* [1957] concluded that there is little to choose between those he compared. He suggested a form

$$u = u_* \ln Z(1 - SRi_0)/(1 - SRi) \tag{17}$$

where $S = 3.5$ (the subscript 0 refers to the Richardson number at height z_0). If this expression is substituted in (1) the fact that Ri is a function of height precludes integration. However, if we define an effective z_0 as

$$z_0^* = z_0(1 - SRi)/(1 - SRi_0) \tag{18}$$

we can use this z_0^* in the equation for the boundary layer height. In (9) we can replace a by $a^* = a(z_0^*/z_0)^{1-n}$. In cases of instability where the Richardson number is negative the result would be $a^* > a$, and hence a higher boundary layer than in the adiabatic case. The opposite would be indicated for stable conditions.

Consider the case where the term SRi_0 is essentially zero and a representative value of $-SRi = 0.7$ (corresponding to $Ri = -0.2$). The value of z_0^* is then 1.7 z_0 which gives $a^* = 1.1a$, indicating only about a ten per cent increase in the value of h.

We will then tentatively conclude that instability leads to a small fractional increase in the height of the boundary layer and that stability leads to a small fractional decrease in the height of the boundary layer, relative to the adiabatic case.

Observations—We should now focus our attention on several observations of boundary-layer heights which have been obtained. Data on the growth of this boundary layer in the atmosphere are indeed scarce. *Glaser* [1955b] obtained wind

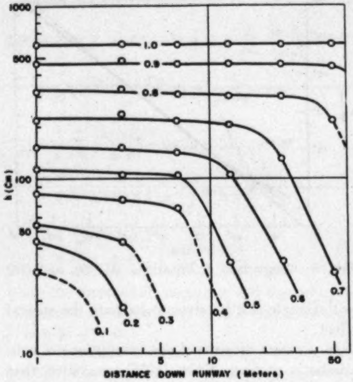

FIG. 4 – Relative wind cross-section [from *Glaser*, 1955b]

profiles along a runway in connection with a study of the temperature structure over a runway on a hot day. We will first briefly describe the equipment used in his study.

A vertical mast was constructed which held eight pairs of anemometers and thermistors, spaced roughly logarithmically with height. The highest pair was approximately six meters above the surface and the lowest pair about ten centimeters above the surface. The anemometers were small three-cup Robinson type, imported from Japan. The instruments were arranged in such fashion that their readings could be recorded in the interior of a converted laundry van. This van towed the entire apparatus so that measurements could be taken at different places with a minimum amount of time lag. Details of the apparatus can be found in reports by *Glaser* [1955a] and *Glaser* and *Elliott* [1956].

The observing site was the Naval Air Station at Houma, Louisiana, which was relatively inactive. The area surrounding the runways was covered with grass about one meter high. The general plan was to await such time as the wind was blowing down the runway. The temperature and wind profiles were first measured at the upwind edge of the runway and at various locations, spaced approximately logarithmically, down the runway. The winds and temperatures reported were averages over five minutes of continuous observation.

From the observed wind speeds it was possible to construct isopleths of wind speed in the xz plane. A segment of this graph for the observation period, August 17, 1955 14h 06m–15h 22mCST, taken from the original work of Glaser, is presented in Figure 4. The isopleths shown are those of the wind speed relative to the six-meter wind. It can be seen that the relative wind-speed isopleths indicate a sharp change in wind speed at different points in the xz plane. The ispoleths can be approximated by two intersecting straight lines except in the region of maximum curvature. The intersection of these lines was taken as the height of the boundary layer, conforming to the original definition. The results of this particular observation period are shown because they present the most clear-cut case of an internal boundary layer. Because of the relative narrowness of runways, slight shifts in wind direction would bring air from the sides across the runways which gives rise to confusion in determining the boundary layer. However, several other observations showed this boundary layer and the same general shape was indicated [see *Glaser*, 1955b].

Figure 5 shows the height of the boundary layer (encircled points) as derived in the above manner. The straight line is the graph of

$$h = 0.86\, x^{0.8} z_0^{0.2}$$

where z_0 has the value 0.02 cm.

It appears that the value of 0.8 for the exponent is in excellent agreement with the observations. The value of z_0 (0.02 cm), obtained from observations of wind profiles over the runway, is quite representative of concrete surfaces. Since z_0 appears to the 0.2 power the final result will not be very sensitive to small errors in z_0. The value of the coefficient is more open to question. The surrounding grass was quite high and the value of z_0 for the grass is somewhat in doubt, but is estimated to be of the order of two or three centimeters. For these reasons only an approximate value of z_0/z_0' can be made. The value of $a = 0.86$, chosen because it best fits the data, falls within the theoretical range of 0.6–0.9. Thus, it appears that the value of 0.8 for the exponent is well verified, while the value for the coefficient is at least in the proper range.

Since these observations were taken on a hot, clear day the temperature gradient was definitely nonadiabatic. However, the value of the exponent remains the same (0.8). Because of the difficulty of obtaining the proper value of z_0/z_0' it is difficult to estimate the true effect of this term. Nevertheless, this result tends to confirm our conclusion regarding the effect of stability, namely, that it is small and that the boundary layer is higher in lapse conditions than it would be in neutral conditions.

Interpretation in terms of smoke plumes—Two other independent observations in this regard seem worth considering. As was mentioned earlier, the original equation was integrated for $m = 1$; that is, no change in z_0. At first glance, this seems to be a fairly meaningless solution since no boundary layer should exist if there is no change in z_0. However, a possible interpretation may be found in considering that the value of h defines the zone of influence of each blade of grass or obstruction to the flow. If each obstruction has the same effect as its neighbor, then no change in the actual flow will occur. But if the obstructions vary in the x direction, then we would expect to find the effect of this variation in roughness reflected in the actual wind field. It appears possible that in the case of no change in z_0 the height of the boundary layer might be shown by the downwind height of a smoke cloud introduced at $x = 0$. If this hypothesis is correct, then observations of the height of a smoke cloud could give values of the height of the boundary layer and also indicate some effects of thermal stratification.

Sutton [1953] reported average data for diffusion from a steady continuous source in small temperature gradients. The only figure cited for the height of a smoke cloud was ten meters at 100 m distance from the source. No value of z_0 was cited, but since the observations were taken over level downland, the value of z_0 probably lies in the range 0.2 to 0.8 cm. Using the formula

$$h = 0.75\, x^{0.8} z_0^{0.2} \tag{19}$$

gives a range of h of 8.6 to 11.3 m, which can be considered very good (a value of z_0 slightly less than 0.5 cm would give $h = 10$ m).

Sutton also presented a derivation of the height of the smoke cloud and found that the height was independent of wind speed and proportional to $x^{7/9}$. The analytical investigation given here is in excellent agreement with Sutton's findings. Sutton stated that his theoretical results had been verified by measurements for small temperature gradients.

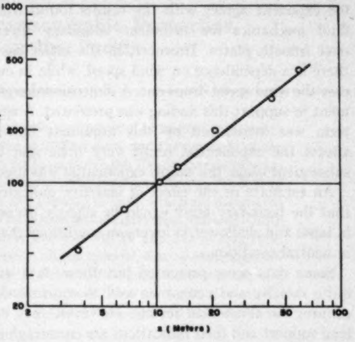

FIG. 5 – Observed and computed growth of internal boundary layer

Another set of diffusion measurements was taken by *Record* and *Cramer* [in press] in connection with the AFCRC Project Prairie Grass. According to them, the plume heights at 100 m from the source averaged 12.5 m in conditions of thermal instability and eight meters in the presence of thermal stability. For the conditions under which these observations were made, the value of z_0 was about 0.7 which would lead to a height of 11 m for average adiabatic conditions. This is again in good agreement with the observations and seems to confirm the hypothesis that instability increases the height of the boundary layer while stability decreases it.

Thermal internal boundary layer—It should also be pointed out here that an analysis similar to the above can be performed for the adjustment of the temperature profile to a new surface temperature in an analogous fashion. This has been performed by *Ogura* [1950] and *Elliott* [1958]. Although their initial assumptions are slightly different, they both arrived at the same equation

$$k^2 x/z_0 = h/z_0 \ln h/z_0 - 3\, h/z_0 + 2 \sum_{n=1}^{\infty} \frac{(\ln h/z_0)^n}{n \cdot n!} + 3 \tag{20}$$

Elliott further showed that this equation could be approximated by

$$h/z_0 = 0.35(x/z_0)^{0.8} \tag{21}$$

which is quite similar to our results for the momentum internal boundary layer. In the Ogura paper one observation is presented which confirms the result in at least one point.

Summary and conclusions—To recapitulate, an expression for the growth of the internal boundary layer has been derived for an adiabatic lapse rate. The resulting expression was approximated by a power-law equation whose exponent is 0.8. This

0.8 exponent agrees with the results found from fluid mechanics for turbulent boundary layers over smooth plates. However, in the latter case, there is a dependence on wind speed, while in our case the wind speed drops out. A dimensional argument to support this finding was presented. A new term was introduced by this argument but it affects the exponential result very little and in subsequent usage the simple exponential was used.

An estimate of the effect of stability indicated that the boundary layer would be slightly deeper in lapse and shallower in inversion conditions than in neutral conditions.

Some data were presented but these data are quite sketchy and cannot be said to conclusively confirm the theoretical results. However, they do lend support and their indications are encouraging.

The need for further observations of the type made by Glaser must surely be apparent. Such measurements made normal to a long discontinuity line would alleviate some of the difficulties encountered along a narrow runway. Perhaps a shoreline or an agricultural field would be adequate.

There is no reason to suppose that such a boundary layer would not be present in the vapor pressure field as well. Under these boundaries the fluxes of momentum and heat change quite radically near the upwind edge and presumably the vapor flux would exhibit similar changes. The presence of the internal boundary layer may contribute to the discrepancies between evaporation pan measurements and the actual evaporation. These considerations are discussed in more detail by *Glaser*, *Elliott* and *Druce* [1957].

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Variations with Depth of Oceanographic Properties Along the Equator in the Pacific

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Abstract—The vertical distribution along the equator in the Pacific of temperature, salinity, density, oxygen, and phosphate, from the sea surface to 1000 meters, and the anomaly of the dynamic height of the sea surface and other isobaric surfaces above the 700-decibar surface are shown. In each of the figures, the available data have been partitioned according to the date of the observation into two periods, July to December and January to June, which are designated in the text as summer and winter, respectively. The figures include data from stations within one degree of latitude north or south of the equator between 110°W and 135°E longitude.

The surface of the sea, relative to the 700-db surface, slopes upward, east to west, approximately 0.8 dynamic meters; the value for the slope is 5.0×10^{-8} during both summer and winter. The longitudinal pressure gradient does not extend much below the layer of relatively large vertical density gradient. At the depth of $\sigma_t = 26.5$, 250–300 m, relatively little east-west slope is evident.

In the surface layer (sea surface to top of the thermocline), temperatures along the equator are lower in the eastern Pacific during both periods; the thermocline is comparatively level west of the 180th meridian, sloping upward to the east of this longitude. Temperatures are appreciably lower and concentrations of inorganic phosphate are higher in the surface layer in the eastern Pacific during the summer, both reflecting the temporal and longitudinal variations in divergence and upwelling.

The oxygen minimum, centered at a depth of approximately 450 m, is a continuous feature from 100°W longitude (eastern limit of the profiles) to near 170°E longitude, with the lowest concentrations in the east (≤ 0.5 ml/L) increasing to 1.5 to 2.0 at the westward limit. West of 170°E longitude, concentrations at 450 m rapidly increase to 3.0 ml/L.

In recent years, numerous profiles illustrating the vertical distribution of properties along meridional (north-south) sections crossing the equator in the Pacific have appeared in the literature. Data thus presented included, for examples, those from cruises of the *Carnegie* [*Sverdrup* and others, 1942], the *Hugh M. Smith* [*Austin*, 1954a; *Montgomery*, 1954; and *King* and others, 1957], the *Albatross* [*Jerlov*, 1956], and various Japanese research vessels [*Mao* and *Yoshida*, 1955]. These data, which were rather widely spaced with respect to both geography and time, were inadequate for consideration of seasonal variations in trans-Pacific vertical profiles, particularly along the equator.

During August through October 1956, 12 vessels participated in EQUAPAC, a quasi-synoptic oceanographic survey of the equatorial Pacific between approximately 20°N and 10°S latitude and 135°W to 135°E longitude. Data from EQUAPAC, plus those from previous and subsequent surveys, now make it possible to study in some detail the vertical distribution and seasonal variations of properties along the equator. In the accompanying figures, profiles for temperature, salinity, density (σ_t), oxygen, and inorganic phosphate, and the anomaly of the dynamic height of the sea surface and other isobaric surfaces above the 700-db surface are shown.

The stations selected for use in the figures were all located within one degree of latitude (60 nautical miles) north or south of the equator. Pertinent information for the stations, each of which has been designated by a letter-number combination on the figures, is listed in Table 1. Wherever available, interpolated data from each station were plotted at standard depths, otherwise observed data were used. In drawing the contours, an effort was made to suppress configurations which apparently resulted from station-to-station temporal variations. This was not always possible without violating plotted values and consequently localized irregularities appear in the isopleths. Some available data were not utilized because they appear to have been recorded during seasons or years which were atypical for their longitude. For example, at *Carnegie* Station 98 near 175°W, the temperatures from the surface to depths somewhat below the thermocline were considerably higher (+6° to +10°C at 200 m) than those for nearby stations, resulting in a pronounced trough in the isotherms.

TABLE 1 – *Pertinent data for oceanographic stations included in Figures 1–6*

Station[a]	Date	Latitude ° ′	Longitude ° ′	Reference
July to December				
Ka 613	Aug. 1, 1956	00 38 N	130 20 E	*Kagoshima University* [1957]
Ke 621	Aug. 2, 1956	01 00 N	135 08 E	*Kagoshima University* [1957]
Sa 32	Aug. 18, 1956	00 29 N	139 49 E	*Suda* [1957]
Sa 14	Aug. 5, 1956	00 30 N	151 02 E	*Suda* [1957]
Ho 31	Aug. 24, 1956	01 00 S	156 46 E	*Scripps Inst. Oceanogr.* [1957]
Ho 10	Aug. 13, 1956	00 02 S	163 57 E	*Scripps Inst. Oceanogr.* [1957]
Or 10	Oct. 4, 1956	00 12 S	170 03 E	Unpublished data; Institut Français d'Oceánie
Or 12	Oct. 13, 1956	00 15 N	176 28 E	Unpublished data; Institut Français d'Oceánie
Dai 21	July 13, 1956	00 10 N	179 57 W	*Shizuoka Pref. Fish. Exp. Sta.* [1957]
St 34	Sep. 15, 1956	00 01 N	174 59 W	*Scripps Inst. Oceanogr.* [1957]
Sm 23	July 10, 1950	01 00 S	171 57 W	*Cromwell* [1954]
St 21	Aug. 29–30, 1956	00 02 N	166 59 W	*Scripps Inst. Oceanogr.* [1957]
Sm 164	Sep. 27, 1956	00 01 S	159 52 W	*Austin* [1957]
Al 111	Nov. 15, 1947	00 02 N	152 07 W	*Bruneau* and others [1953]
Sm 32	Sep. 27, 1951	01 00 S	149 58 W	*Austin* [1954a]
Sm 113	Sep. 2, 1956	00 02 N	143 03 W	*Austin* [1957]
Sm 144	Nov. 20, 1955	00 16 N	140 11 W	*King* and others [1957]
Sm 62	Aug. 19, 1956	00 04 S	134 54 W	*Austin* [1957]
Sm 94	Nov. 7, 1955	00 11 S	119 58 W	*King* and others [1957]
Ba 23	Oct. 12, 1955	00 58 N	116 03 W	*Scripps Inst. Oceanogr.* [1956]
Sm 73	Oct. 31, 1955	00 12 S	112 25 W	*King* and others [1957]
Da 3558	Sep. 18, 1928	00 18 S	99 07 W	*Thomsen* [1937]
Ba 58	Nov. 28, 1955	00 00	91 41 W	*Scripps Inst. Oceanogr.* [1956]
Ba 51	Nov. 15, 1955	00 00	83 47 W	*Scripps Inst. Oceanogr.* [1956]
January to June				
Ja 97	June 14, 1938	00 49 N	149 54 E	Unpublished data, U.S.N. Hydrogr. Of.
Ja 101	June 17, 1938	00 48 N	153 49 E	Unpublished data, U.S.N. Hydrogr. Of.
Al 143	Jan. 3, 1948	00 09 S	163 23 E	*Bruneau* and others [1953]
Sm 25	Feb. 18, 1952	00 02 N	179 59 E	*Stroup* [1954]
Ca 98	Apr. 30, 1929	00 18 N	173 59 W	*Fleming* and others [1945]
Sm 40	Mar. 4, 1952	00 01 N	169 00 W	*Stroup* [1954]
Sm 35	Feb. 20, 1950	00 04 S	158 22 W	*Cromwell* [1951]
Sm 9	Jan. 31, 1952	00 06 S	155 14 W	*Stroup* [1954]
Sm 88	Mar. 20, 1957	00 01 N	145 02 W	*Wilson* and *Rinkel* [1957]
Sm 22	June 5, 1952	00 43 S	140 11 W	*Austin* [1954b]
Sm 43	Feb. 25, 1957	00 00	130 00 W	*Wilson* and *Rinkel* [1957]
Sm 3	Jan. 23, 1957	00 03 N	123 17 W	*Wilson* and *Rinkel* [1957]
Sm 6	Jan. 24, 1957	00 22 N	120 11 W	*Wilson* and *Rinkel* [1957]
Sm 12	Jan. 26, 1957	00 06 N	113 54 W	*Wilson* and *Rinkel* [1957]
Sm 15	Jan. 27, 1957	00 12 S	110 12 W	*Wilson* and *Rinkel* [1957]

[a] Al, *Albatross*; Ba, *Spencer F. Baird*; Ca, *Carnegie*; Da, *Dana*; Dai, *Daifuji Maru*; Ho, *Horizon*; Ja, Jap. 90029; Ka, *Kagoshima Maru*; Ke, *Keiten Maru*; Or, *Orsom III*; Sa, *Satsuma*; Sm, *Hugh M. Smith*; and St, *Stranger*.

There are two profiles for each of the fields depicted, one for the period July to December, the other for January to June. These two periods, for simplicity of terminology and discussion in the subsequent text, have been designated as 'summer' and 'winter,' respectively, without implication as to the summer and winter seasons recognized in higher latitudes. The division of the year into the two six-month periods resulted primarily from consideration of the seasonal variability in the trade winds and also from the necessity of selecting periods within which there would be a sufficient number of stations to provide adequate data for the sections. The southeast trades (of particular significance along the equator) are at maximum constancy and force in August–September, minimum in March–April.

Vertical profiles along the equator are of diversified interest. As expressed by *Montgomery* and *Palmén* [1940], the equator is the ideal location for determining the longitudinal pressure gradient. At the equator there can be no cross-stream gradient because deflecting force and compensating pressure gradient both vanish. Of interest to both the physical oceanographer and the marine biologist are the east-west (and seasonal) variations in the

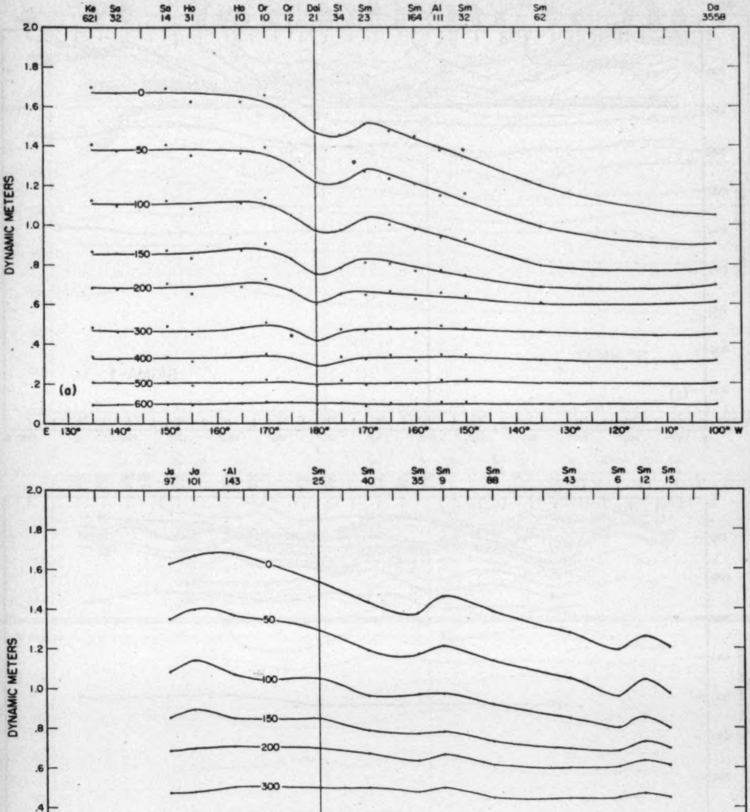

FIG. 1 – Anomaly of the dynamic height of the sea surface and other isobaric surfaces above the 700-db level; (a) July to December; (b) January to June; see Table 1 for position, date, and source of data for each station designated along the top borders

slope of the thermocline and of the equatorial divergence and upwelling.

In Figure 1 we have shown the anomaly of the dynamic heights for the sea surface and other isobaric surfaces, all relative to the 700-db assumed level of no motion. During both periods, the sea surface slopes upward, east to west, with a mean value for the slope of 5.0×10^{-8} (0.8 m in 15×10^3 km) during both the summer and the winter. ***Montgomery*** and ***Palmén*** [1940] calculated the slope to be 4.5×10^{-8}.

Between the two periods there are variations in

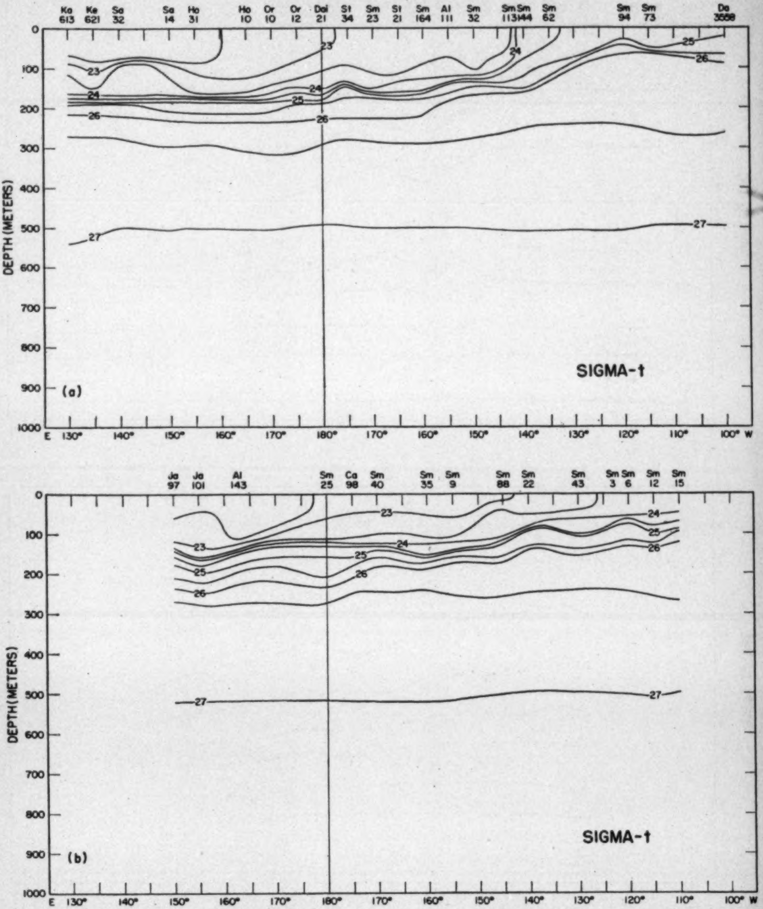

FIG. 2 – Density; contour interval 0.5 units of sigma-*t*; (a) July to December; (b) January to June

the height of the sea surface in the eastern Pacific. During the summer, east of approximately 165°W longitude, the surface is 10–15 dynamic centimeters lower (relative to the 700-db surface) than during the winter. The dips in the anomaly of the dynamic height of the sea surface near 180° in the summer and 165°W in the winter are difficult to explain. Enough stations are involved in each case to suggest that they are a real feature.

Montgomery and *Palmén* [1940, Fig. 43] demonstrate that the longitudinal pressure gradients in the Atlantic and the Pacific do not extend below the layer of relatively large vertical gradient in density (hereinafter referred to as the stable layer).

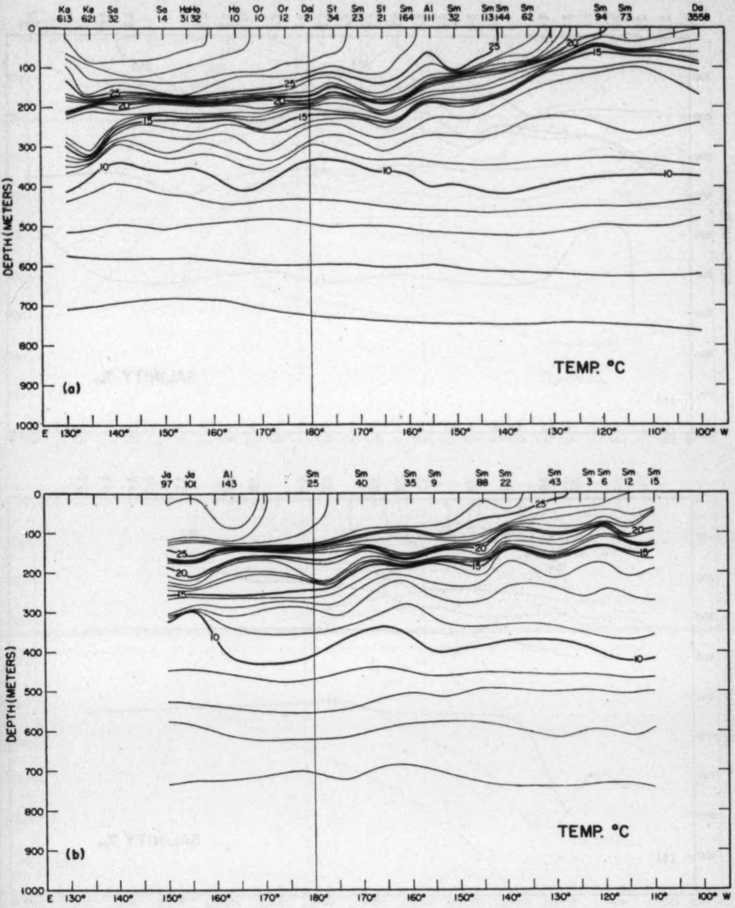

FIG. 3 – Temperature; contour interval 1°C; (a) July to December; (b) January to June

For their analyses of the situation in the Pacific, data for only two positions were available, one at 99°07′W, the other at 134°44′E longitude. Using the data from the stations included in Figure 1, the σ_t distribution along the equator is shown in Figure 2. Although, when comparing Figures 2a and 2b, variations in density are evident in the surface layer (surface of the sea to top of the stable layer) and in the east-west slope of the stable layer, the 26.5 isopleth (250–300 m) in both figures shows relatively little east-west slope.

During the summer, the east-west slope of the stable layer is steeper than in the winter east of 160°W; conversely to the west of 160°W, the slope

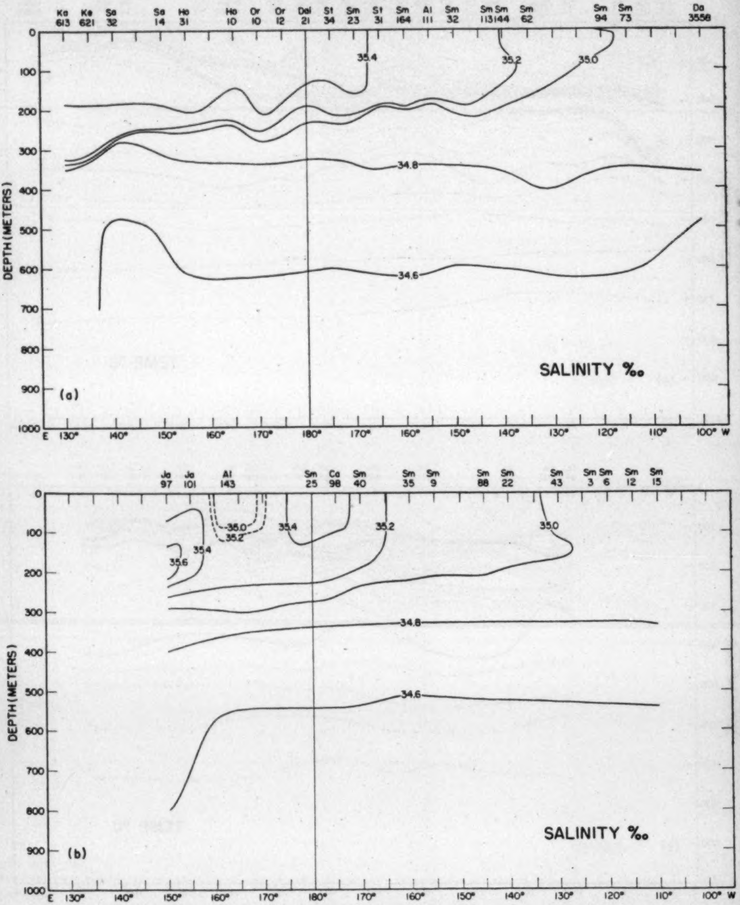

FIG. 4 – Salinity; contour interval 0.2 per mille; (a) July to December; (b) January to June

is less in summer than in winter. In terms of depth of the stable layer, in the west it is deeper and in the east shallower in summer than in winter. These variations, evident in Figure 2 (and 3), reflect the greater volume of lighter, warmer water in the western Pacific during the July to December period.

Variations in density and thus in the results of the geostrophic calculations in the tropical Pacific are principally a function of variations in temperature. The vertical distribution of temperature is shown in Figure 3. In general, the temperatures in the surface layer are cooler in the eastern Pacific than in the west; the thermocline is comparatively

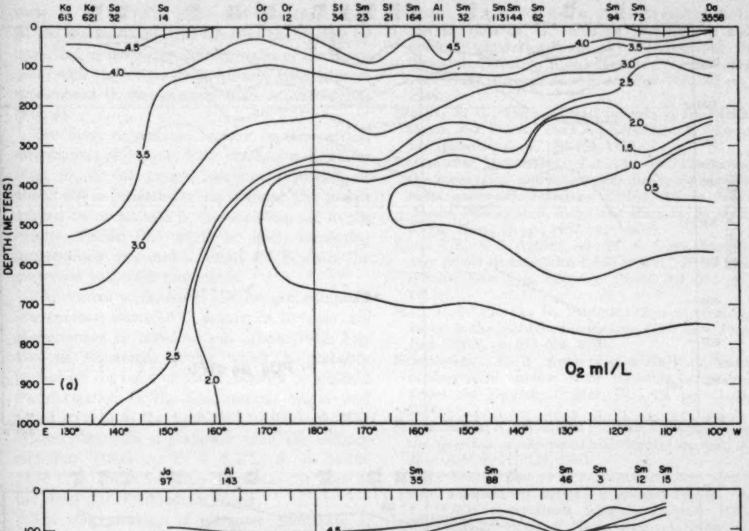

FIG. 5 – Oxygen; contour interval 0.5 milliliters per liter; (a) July to December; (b) January to June

level in the western Pacific, sloping upward east of the 180th meridian [*Sverdrup* and others, 1942, Fig. 197]. During the summer period, particularly in the eastern Pacific, the temperatures of the surface layer are considerably cooler than during the winter, while in the west, summer temperatures are warmer to greater depths.

Austin and *Rinkel* [1957], in part through a comparison of meridional temperature sections, have shown that there is an east-west variation in upwelling at or near the equator in the Pacific with the maximum mixing of the deeper, cooler waters with those at the surface being in the eastern central Pacific. In addition, they state

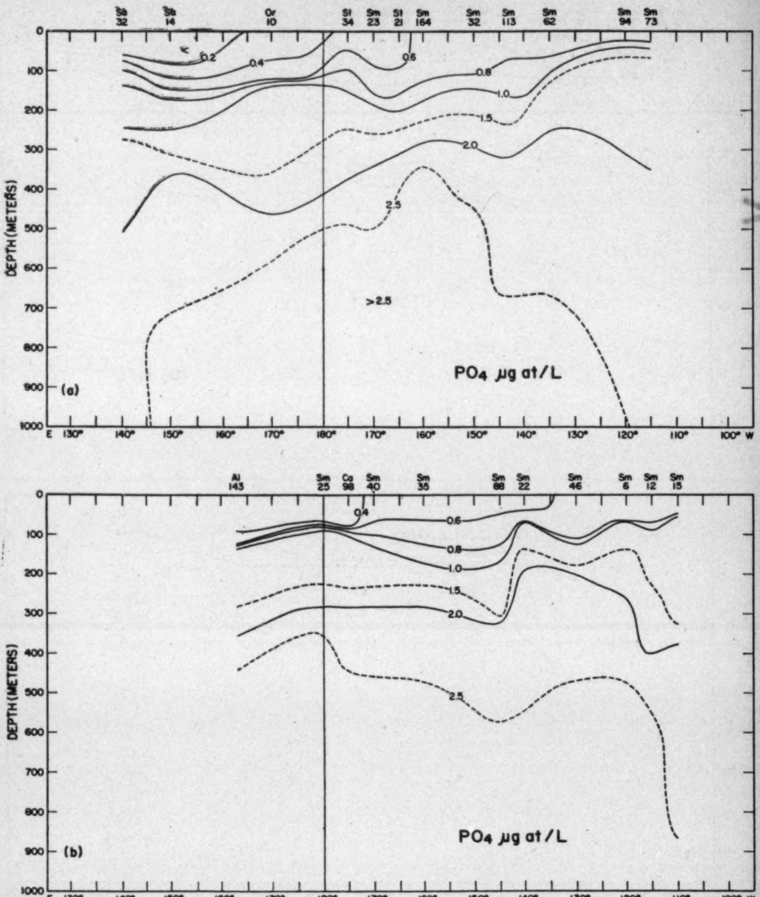

FIG. 6 – Inorganic phosphate; contour interval 0.2 for concentrations less than 1.0 microgram atoms per liter; 0.5 for concentrations greater than 1.0 microgram atoms per liter; (a) July to December; (b) January to June

that the period of most active upwelling is during August through October, the period of the maximum constancy and force of the easterly component of the southeast trade winds. These conclusions are reflected in the cooler surface waters in the eastern portion of Figure 3a.

The more active upwelling in the eastern Pacific during the summer is also reflected in the vertical distribution of salinity (Fig. 4). In the eastern Pacific, the mixing processes associated with upwelling limit the penetration of the waters of the intermediate salinity maximum into the northern hemisphere [*Austin*, 1954b; *Austin* and *Rinkel*, 1957]. In the western Pacific, these waters penetrate to 5° to 10°N [*Mao* and *Yoshida*, 1955]. In the eastern Pacific the effect of the mixing by upwelling of the higher salinity water of the maximum with the waters in the surface layer is more pronounced in the summer than in the winter (Fig. 4).

The most pronounced feature in the vertical distribution of oxygen, both summer and winter (Fig. 5), is the oxygen minimum centered at about 450 m beneath the sea surface. The lowest oxygen concentrations in the minimum are in the eastern Pacific (0.5 ml/L or less), increasing progressively westward to about 165°E where the minimum essentially terminates.

The waters at depths of the oxygen minimum (temperature about 9.0°C, salinity 34.70 $^0/_{00}$) are characterized by *Sverdrup* and others [1942, Fig. 196] as Equatorial Water which is probably formed off the coast of South America by gradual transformation of the Subantarctic Water and which spreads to the north and to the west. The oxygen minimum is shallower than the salinity minimum (1000 m, $T = 5.5°\mathrm{C}$, $S = 34.50$–34.58 $^0/_{00}$) which Sverdrup denotes as the 'core' of the Antarctic Intermediate Water.

The concentrations of inorganic phosphate in the surface waters (Fig. 6) are comparatively higher in the eastern Pacific, 0.6–0.8 μg at/L as compared with $\leq$0.2 μg at/L in the western half of the ocean. In general, east of 160°W they are higher during July to December, the period of most intensive upwelling.

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Statistics on Wave Heights and Periods for the North Atlantic Ocean

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Abstract—This paper gives the frequency distributions of wave heights and wave periods obtained from weather ships stationed in the North Atlantic, together with an evaluation of the reliability of the visual wave-height estimates comprising the basic data from which the distributions are derived. Visual estimates are compared with values determined from stereophotographs. An additional check is provided by wave-meter measurements. It is shown that a log-normal distribution is applicable to the frequency distribution of wave heights experienced over a typical year and that this distribution is a useful guide to the determination of the incidence of a particular sea state at a given location.

Data from weather ships—Wave heights and periods for ten ocean stations were obtained from U. S. Weather Bureau records. These data are visual estimates covering a period of six years and were made every three hours by trained weather observers. By international agreement, all ocean-station vessels use the same methods of estimating, as described by the *U. S. Weather Bureau* [1950; pp. 57–58]. Only one quantitative value for wave height and one for wave period were reported each time the sea was observed.

Visual estimates for correlation against stereo data—In order to evaluate the accuracy of the visual wave estimates and their usefulness in the statistical analyses, stereocameras were installed on one of the weather ships, the USCGC *Unimak* (WAVP 379), and on the USS *Valley Forge* (CVS 45).

Visual estimates of the sea surface were made by trained observers at the same times that stereophotographs were taken. The *Unimak* estimates were made by regularly assigned Weather Bureau observers. The *Valley Forge* estimates were made by trained Navy aerological personnel; two or more of them made independent estimates twice each hour during most observation periods. By special arrangement, five or six of the Navy aerological personnel made independent wave estimates three times each day. Subsequently, the *Valley Forge* estimates were averaged and plotted against time of observation and a smooth curve was fitted to these points. From these curves, characteristic wave heights were obtained and are entered in Column 7 of Table 1.

The times shown in Columns 3 and 4 of Table 1 are local civil time values for the time zone in which each observation was taken. Each of the ship positions shown in Column 4 of Table 1 was obtained from the vessels' regularly developed navigation data; positions shown are those that were closest in time to each of the observations of wave data.

In making their observations, the Weather Bureau personnel on the *Unimak* followed the instructions of the *U. S. Weather Bureau* [1950], which specifies "larger, well-formed waves." The Navy observers were guided by the *U. S. Hydrographic Office* [1955], which calls for "higher, well-defined waves." It is apparent that the estimating procedures specified by these two different organizations are essentially the same.

Throughout this report the term 'characteristic height' will be used to denote *the average height of the higher, well-defined waves*. The statement italicized will serve as a definition of this quantity. The term 'significant wave height' will be used only in its statistical sense *as the average of the ⅓ highest waves*. The 'characteristic wave period' is *the average period* of the higher well-defined waves.

Data from sea surface profiles—Of the many hundred stereophotograph pairs taken during the sea trials, 60 were selected for analysis to cover as wide a range of sea conditions as practicable. Each of these was converted into sea-surface profiles by photogrammetric specialists at the Naval Photographic Interpretation Center or Navy Hydrographic Office. The Wild A5 Autograph and Zeiss Stereo Planigraph Model C5 were used by the respective agencies, and vertical mapping techniques were adapted to this horizontal application. Next, the sea-surface profiles were analyzed by the Oceanographic Division of the Hydrographic Office. The accuracy of a wave profile varies with the distance from the camera to the profile. The average accuracy is about ±0.5 ft at a distance of 2000 ft and is better than this at shorter distances.

The sea-surface profiles were used to determine the characteristic wave heights by following the same general procedure as that used by the shipboard observers in making their estimates; thus these two independent determinations of characteristic wave height should be comparable. These values are shown in Column 9 of Table 1.

Statistical background—Wave heights and wave periods from the weather-ship data for ten ocean stations are presented in the form of their distribution functions. For example, all wave heights reported by the shipboard observers are considered to be members of a statistical population of wave heights. The distribution function of wave heights indicates the relative probability of encountering a wave of a given height as a function of that height. Figure 1 illustrates this distribution function. The area under the curve to a value x_i is the integral of the function up to x_i and is equal to the fraction of all members of the population of wave heights which have a height less than x_i. Mathematically

$$P(x) = \int_0^x p dx \quad \text{and} \quad P(x \to \infty) = \int_0^\infty p dx = 1$$

where p is the probability density and P is a function of x designated as the cumulative distribution function of x. $P(x)$ is numerically equal to the probability that a value chosen at random from the population is less than x.

A detailed discussion of the statistical methods utilized in this report is given by *Jasper* [1956]. Only a few of the major concepts will be described here. The distribution applicable to a given sea condition is here called a 'short-term' distribution, whereas the distribution applicable when the sea conditions are allowed to vary over a wide range, such as over a year's time, is called a 'long-term' distribution. Thus the long-term distribution is the result of a summation of a number of short-term distributions. Oceanographers have held that the short-term distribution of wave heights x is approximately of the Rayleigh type (a narrow power-spectrum is assumed) for which

$$p(x) = \frac{2x}{E_i} e^{-x^2/E_i}$$

where E_i is the mean square of all the individual wave heights x corresponding to sea condition i. Note that numerically the value of E computed for wave height will be four times the value of E computed for wave amplitude because wave height is taken equal to twice the wave amplitude. See *Pierson* and others [1955] and *St. Denis* and *Pierson* [1953] for a discussion of the distribution of wave heights in terms of the power-spectrum concept. The short-term distribution is approximately valid if measurements are taken over a relatively short period of time, of the order of one hour, during which interval the sea conditions do not change appreciably. It can be shown that this distribution is the same as that representing the wave heights, in the area under consideration, at one instant of time.

Jasper [1956] suggested that the long-term distribution of wave heights and wave periods is of the log-normal type, that is, that the logarithms of these heights and periods are approximated by a normal distribution. Thus

$$p(\log x)d(\log x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-(\log x - u)^2/2\sigma^2} d(\log x)$$

$$P(x) = P(\log x) = \int_{\log x = -\infty}^{\log x} p(\log x)d(\log x)$$

where $p(\log x)$ is the probability density of the variate, $\log x$, u is the mean value of $\log x$, and σ^2 is the variance of $\log x$. Then the parameters u and σ define this distribution completely.

In this report log-normal distributions are fitted to the characteristic wave heights and periods reported by the weather ships. The resultant graphs give the probability with which a given value of the variate x will or will not be exceeded in an average year. Although the distributions given here are for a six-year period, study of distributions for individual years making up the six-year period indicates that a single year gives a

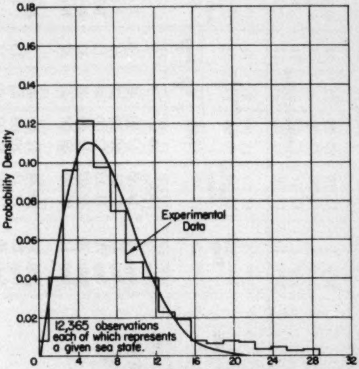

FIG. 1 – Distribution function of wave heights

TABLE 1 – *Correlation of wave data with ship positions*

	Stereophotographs						Visual observations made aboard ship			DTMB stereoanalysis				USN Hydrographic Office stereoanalysis				
Ship	Date	Time of photo	Position			Stereophoto and sea surface profile number	Number of estimators	Characteristic wave height, (Average of larger waves)		Number of largest waves N		Characteristic wave height (Average of larger waves)		Number of waves in sample	Cutoff wave length	Significant wave height	E^a (estimated from wave height)	E^a (estimated from wind data)
			Time	Lat. N	Long. W			Sea	Swell	Sea	Swell	Sea	Swell					
1955		h m	h m	°	°			ft	ft			ft	ft		ft	ft	ft²	ft²
CVS 45	Sep. 11	14 35	12 00	40	58	A-0119	3	5.0	...	12	12	5.4	6.5	200	23	3.6	6.6	13.6
	Sep. 12	17 01	20 00	40	51	A-0200	4	4.8	...	11	7	4.4	6.9	197	18	4.2	8.3	9.2
	Sep. 20	11 13	12 00	45	17	B-0163	4	...	9.3	11	15	6.1	11.6	201	42	7.2	25.6	20.0
	Sep. 20	12 02	12 00	45	17	B-0165	3	...	8.0	12	6	9.6	10.0	199	33	6.8	23.6	32.0
	Sep. 15	09 25	08 00	43	37	B-0218	2	7.2	...	25	12	6.3	5.9	200	32	4.1	14.3	24.0
	Sep. 22	14 34	12 00	48	8	C-0233	3	...	10.0	11	7	5.9	11.2	198	42	6.1	17.0	28.0
	Sep. 28	17 15	20 00	42	13	C-0418	4	...	9.0	11	14	5.5	9.0	200	..	5.3	12.5	24.0
	Sep. 30	11 00	12 00	40	15	C-0452	3	...	8.0	12	21	6.6	8.6	182	30	5.9	17.2	32.0
	Sep. 30	14 17	12 00	40	15	C-0466	3	...	7.7	12	12	8.1	8.2	161	34	6.0	17.7	24.0
	Sep. 30	15 15	12 00	40	15	C-0470	3	...	7.8	12	15	9.1	7.5	209	..	4.4	8.9	24.0
	Oct. 1	12 45	12 00	43	13	C-0495	6	...	9.0	12	16	5.8	7.0	196	31	4.2	10.7	28.0
	Oct. 1	14 15	12 00	43	13	C-0500	3	...	8.8	10	11	6.3	8.0	110	34	6.0	14.3	32.0
	Oct. 2	13 00	12 00	39	13	D-0017	3	...	4.4	12	8	2.8	4.5	177	20	3.4	5.1	9.2
	Oct. 11	09 48	08 00	37	15	D-0085	5	...	6.2	15	11	4.2	5.4	208	21	3.7	6.1	10.4
	Oct. 11	16 16	20 00	37	18	D-0122	7	...	8.0	16	8	6.2	6.5	241	20	4.8	9.9	12.0
	Oct. 12	08 12	08 00	36	21	D-0148	6	...	5.5	14	5	8.5	5.4	223	..	6.7	19.6	18.0
	Oct. 12	09 46	08 00	36	21	D-0159	5	...	5.0	13	10	7.1	6.7	184	20	5.6	13.6	9.2
	Oct. 12	16 00	20 00	35	22	D-0199	3	...	6.9	10	14	6.5	6.3	190	..	4.3	8.9	16.0
	Oct. 13	10 46	08 00	35	26	E-0017	5	...	4.0	10	8	2.2	3.5	184	..	2.1	2.1	5.2
	Oct. 13	12 15	12 00	35	27	E-0021	7	...	3.7	12	7	5.6	4.5	200	..	3.3	5.3	5.2
	Oct. 13	16 46	20 00	35	29	E-0034	7	...	2.3	13	..	5.0	...	148	30	4.5	8.9	5.2
	Oct. 14	13 15	12 00	34	34	E-0062	3	...	6.1	10	5	7.2	7.1	200	26	5.2	11.8	16.0
	Oct. 14	13 45	12 00	34	34	E-0064	3	...	6.1	15	12	6.9	6.9	199	26	5.9	15.8	16.0
	Oct. 14	14 15	12 00	34	34	E-0068	4	4.6	6.0	..	..	...	...	180	33	6.0	17.0	16.0
	Oct. 14	14 45	12 00	34	34	E-0071	4	...	6.0	10	14	6.9	5.9	178	28	3.4	9.3	18.0

	Oct. 14	15 15	20 00	34	35	E-0074	3	...	5.9	17	12	7.3	6.5	200	..	4.9	11.3	18.0
	Oct. 16	06 45	08 00	34	45	E-0145	1	...	10.3	13	9	8.0	10.4	148	42	5.4	18.4	24.0
	Oct. 17	09 45	08 00	35	57	F-0222	4	...	7.3	16	10	4.1	5.7	200	..	5.2	7.1	20.0
	Oct. 18	12 45	12 00	35	59	F-0289	4	...	6.1	15	..	5.6	...	200	26	3.3	6.8	16.0
	Oct. 19	10 15	12 00	35	67	F-0344	4	4.8	...	12	9	5.8	5.1	176	25	5.0	11.6	13.6
	Oct. 19	14 45	12 00	35	67	F-0362	4	...	6.6	11	3	9.2	6.3	166	30	5.9	15.9	20.0
	Oct. 19	15 51	20 00	35	68	F-0365	1	7.7	...	13	4	8.2	11.0	150	26	6.0	15.3	20.0
	Oct. 20	17 15	20 00	36	71	G-0049	5	...	3.7	15	7	5.0	5.0	163	23	4.4	9.1	8.0
	Oct. 22	07 15	08 00	37	71	G-0113	4	...	5.9	14	11	5.7	5.1	200	26	4.8	10.4	20.0
	Oct. 22	12 15	12 00	36	72	G-0127	6	...	6.6	15	10	5.5	6.7	63	40	6.1	19.8	16.8
	Oct. 22	16 17	20 00	37	73	G-0150	2	...	6.5	14	8	4.2	7.1	200	..	4.1	8.1	18.4
	Nov. 15	07 50	08 00	37	73	H-0047	2	...	3.7	12	9	3.6	3.9	200	..	3.2	5.0	5.2
	Nov. 15	09 50	08 00	37	73	H-0060	2	...	2.7	14	10	3.6	3.7	181	20	3.3	4.6	9.2
	Nov. 15	10 55	12 00	38	73	H-0078	4	...	2.7	14	..	3.8	...	162	20	2.5	3.0	9.2
	Nov. 15	11 15	12 00	38	73	H-0087	1	...	2.7	14	10	2.9	3.7	200	..	2.8	3.5	9.2
	Nov. 15	11 55	12 00	38	73	H-0100	3	...	2.8	14	12	3.5	4.5	200	20	3.4	5.2	9.2
	Nov. 16	07 15	08 00	37	72	H-0155	6	...	3.6	14	15	6.0	5.3	188	20	5.1	12.0	9.2
	Nov. 16	12 55	12 00	37	72	H-0201	2	...	7.0	16	11	5.1	5.3	169	30	5.2	11.9	32.0
	Nov. 16	15 45	20 00	37	72	I-0014	3	...	7.5	16	13	6.4	7.9	148	32	6.9	22.0	30.0
	Nov. 17	08 15	08 00	37	74	I-0052	5	...	7.1	20	13	3.8	6.0	200	..	4.6	9.7	18.4
	Nov. 17	13 45	12 00	37	74	I-0073	2	...	4.3	17	12	4.3	6.0	200	..	4.6	10.3	10.4
	Dec. 9	15 30	12 00	36	70	J-0003	4	10.5	9.9	16	11	7.3	9.3	139	34	6.8	21.5	24.0
	Dec. 10	09 45	08 00	36	72	J-0035	3	12.5	12.7	18	9	15.3	12.2	144	38	8.1	29.4	40.0
	Dec. 10	10 45	12 00	36	72	J-0040	3	12.0	12.1	13	..	16.8	...	150	40	10.9	58.8	48.0
WAVP 379	Oct. 16[b]	16 29	15 00	44	41	U-359	1	13.0	...	14	..	11.6	...	146	..	9.4	...	...
	Oct. 22[b]	13 18	12 00	44	41	U-415	1	5.0	...	11	..	7.1	...	31	..	5.5	...	...
	Jan. 16	12 40	12 00	57	51	U-505	1	14.0	...	10	..	14.7	...	91	..	8.1	...	...
	Jan. 16	16 28	15 00	57	51	U-517	2	19.5	...	10	..	21.6	...	87	..	9.0	...	...
	Jan. 28	15 16	15 00	57	51	U-525	2	5.5	...	20	..	6.5	...	90 66 } 156	..	5.1 6.9 } 6.2	...	...
	Jan. 28	15 36	15 00	57	51	U-526	2	5.5	...	8	..	8.4	...		..		...	...
	Jan. 31	12 26	12 00	57	51	U-537	1	18.0	...	7	..	15.8	...	37	..	8.2	...	...
	Feb. 1	12 20	12 00	57	51	U-540	1	16.0	...	12	..	17.3	...	111	..	7.4	...	...
	Feb. 1	12 21	12 00	57	51	U-541	1	16.0	...	8	..	20.7	...	33 } 258	..	12.0 } 7.9	...	...
	Feb. 1	12 22	12 00	57	51	U-542	1	16.0	...	12	..	17.4	...	114	..	7.2	...	...
	Feb. 2	12 18	12 00	57	51	U-548	1	18.0	...	9	..	19.1	...	34	..	8.4	...	...

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[a] *E* is the mean square value of wave heights.

[b] 1954, not 1955.

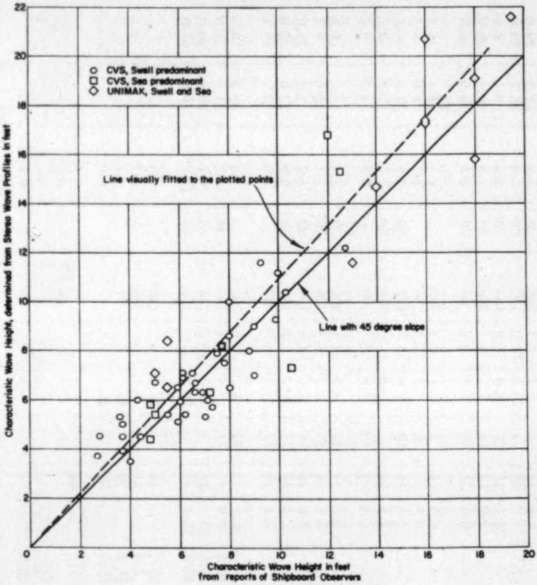

FIG. 2 – Scatter diagram for comparison of characteristic wave heights determined independently from the wave-profile analysis and by shipboard observers; data from Table 1, Columns 7 and 9

typical sample of the distribution obtained for many years. Therefore, the six-year distribution may be considered valid for an average year.

Evaluation of reliability of visual estimates of wave heights—The characteristic wave heights obtained by the shipboard observers are compared with those derived from the stereograms for the same sea condition in Figure 2, where values from Columns 7 and 9 of Table 1 are plotted as abscissas and ordinates, respectively. If exact agreement existed between visual estimates and the results of photogrammetric analysis, then all points would lie on a straight line with a 45° slope. The points plotted in Figure 2 scatter fairly well about a straight line which has a slope somewhat greater than 45°. The average deviation of the points from the line is expected to decrease as the number of points is increased. It should be noted that each stereophotograph covers a limited field of view compared with the field of view of the shipboard observer (Fig. 3).

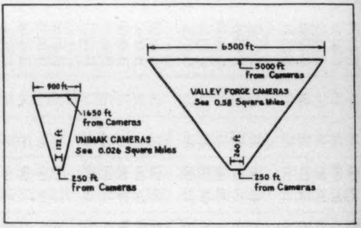

FIG. 3 – Ocean perspectives seen by stereocameras on *Unimak* and *Valley Forge* (areas indicated are fixed by properties of cameras, film, stereoplanigraphs, and camera separation).

It is considered that Figure 2 shows good correlation between the visual estimates and quantitative height determinations made from the stereophotographs. Individual estimates may not be accurate, but when the number of estimates is large the correlation is good.

The *Unimak* data and the *Valley Forge* data do not indicate divergent trends, that is, although the observers on the *Unimak* and the *Valley Forge* used slightly different criteria for observing waves, their results are substantially identical.

The visual observations on which the long-term distributions given later in this report are based, comprise between 11,000 and 18,000 separate observations for each ocean station. It is concluded

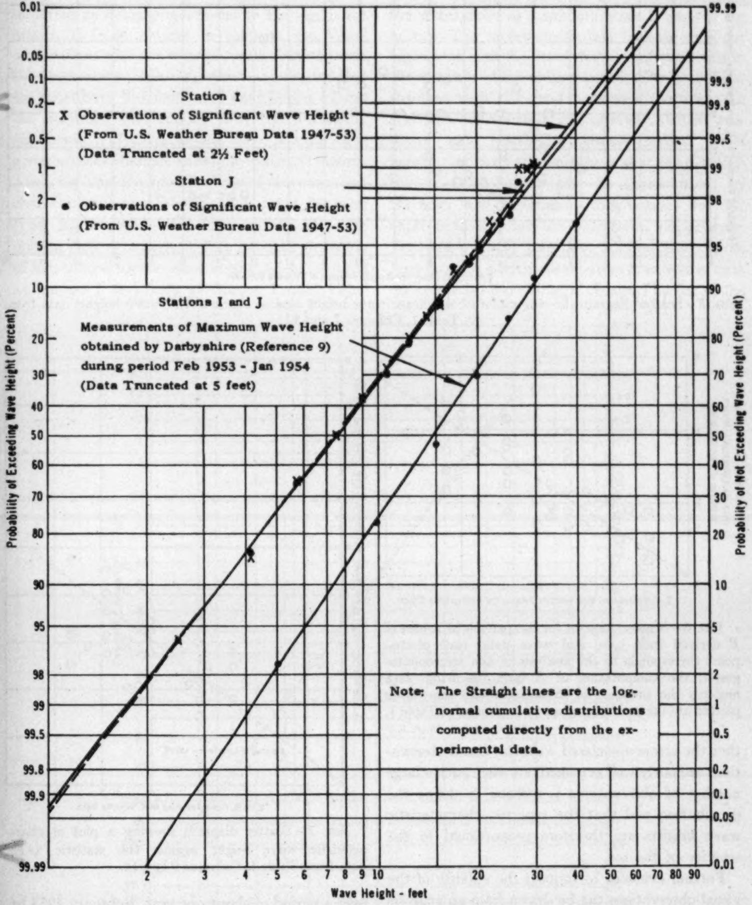

FIG. 4 – Comparison of wave-height distributions derived from visual observations and from measurements of wave heights at Atlantic Ocean Stations I and J; the distribution fitted to the Darbyshire data corresponds to a standard deviation of 0.57 for log$_e$ (maximum wave height) and a median value of the maximum wave height equal to 15 ft.

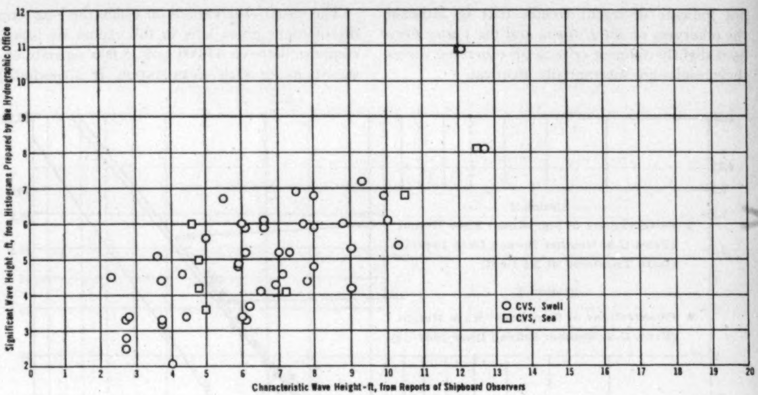

FIG. 5 - Scatter diagram showing a plot of significant wave height against characteristic wave height; data from Table 1, Columns 7 and 12

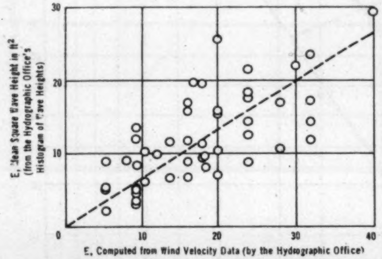

FIG. 6 - Scatter diagram for comparison of values of *E* derived from wind and wave data; each plotted point corresponds to the analysis of one stereophotograph; the computation of *E* from the wind data neglects the presence of decaying swell; the values plotted are taken from the last two columns of Table 1.

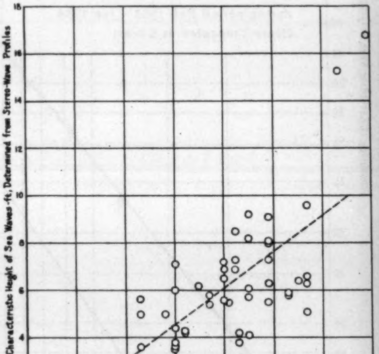

FIG. 7 - Scatter diagram showing a plot of characteristic wave height against the statistic $\sqrt{E}$; data from Table 1, Columns 9 and 14.

that the errors associated with the visual observations are fairly well averaged out when such a large number of observations is utilized to define the distribution and that the reported characteristic wave heights are therefore proportional to the severity of the sea.

Further evidence to support the validity of the visual observations can be drawn from an analysis of measurements of wave height made by *Darbyshire* [1955] by means of a wave meter installed on a weather ship. These measurements were made over a period of about one year, February 1953 to January 1954, at North Atlantic Weather Stations I and J (Fig. 4). Darbyshire reported the maximum wave height for each three-hour period for which visual wave observations were made while the ship was at sea. The visual observations made by weather observers are reported as the 'characteristic' wave height. In the discussion of Figure 5 in the following section, the characteristic height is indicated as being proportional to the significant height. It is of interest to compare the visual observations with the measurements obtained with the wave meter. If the hypothesis is accepted that the short-term distribution of wave height follows the Rayleigh distribution, then the maximum, significant, and characteristic wave heights for a given sea condition are related by constant factors. Thus, the long-term distributions of maximum and characteristic wave heights should be of the same type, log-normal in this case, and should differ only in their mean values. The standard deviation of $\log_e$ (characteristic wave height in feet) is 0.622 at Station J and 0.612 at Station I from visual observations, as compared with a value of 0.57 for $\log_e$ (maximum wave height) for the measurements at Station I and J reported by Darbyshire (Fig. 4). A log-normal distribution has been fitted to the wave-meter data on the assumption that the distribution of maximum wave heights is log normal. The experimental data indicate excellent agreement with the fitted distribution, well within the accuracy of the measurements. The latter fact, together with the good agreement between the standard deviations of characteristic (visual estimates) and maximum (measurements) wave heights, supports the hypothesis that the distribution of wave heights may be approximated by Rayleigh and log-normal distributions for the short term and for the long term, respectively. *Darbyshire* [1956] tests the applicability of the long-term log-normal distribution to extensive data on maximum wave heights obtained by use of the

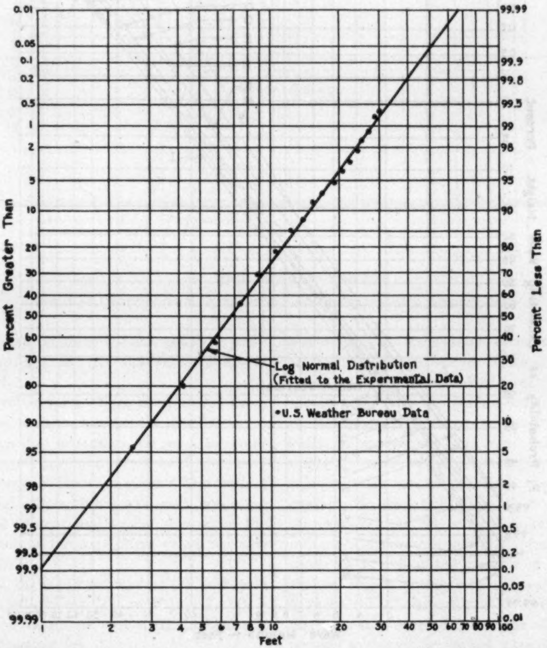

FIG. 8 – Distribution of characteristic wave heights at Station C

British wave meter. He concludes that the logarithmic law appears to be a useful guide to determine the incidence of a particular wave state at a given location.

It is concluded on the basis of the foregoing discussion that the visual estimates by weather observers of sea state, reported as a 'characteristic' wave height, may be used with confidence in establishing distribution patterns such as are given in a following section.

Comparison of wave statistics—It is of interest to utilize the wave data obtained during the sea tests of the *Valley Forge* and the *Unimak* to gain some insight into the validity of a few of the assumptions often made in the forecasting and analysis of ocean waves. For this purpose, the following items were computed:

(a) The characteristic wave height was determined from the wave profiles.

(b) The wave profiles were analyzed statistically to obtain the frequency distribution of individual wave heights and of the corresponding wave lengths above a certain cutoff length, which is that wave length below which lies three per cent of the area under the power spectrum.

(c) The mean value of the squares of all individual wave heights corresponding to waves longer than the cutoff length was determined from the data obtained under (b). These values are denoted by the symbol E, and are listed in Table 1.

(d) The average value of the upper third of the waves having the largest magnitudes (significant wave height) was determined from the data obtained under (b).

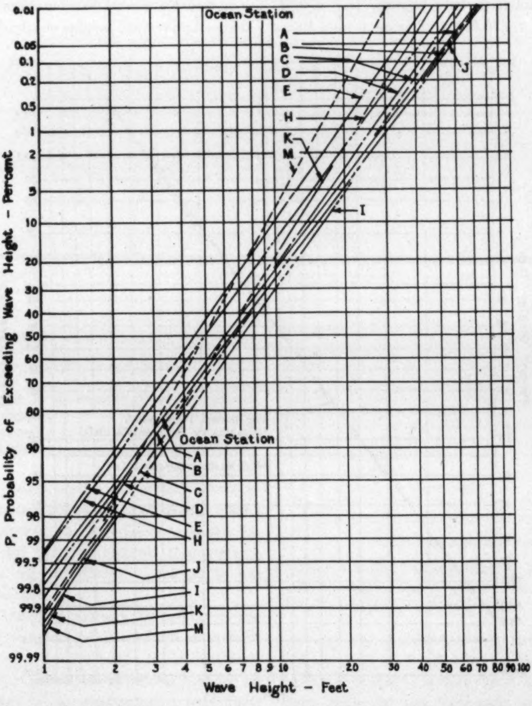

FIG. 9 – Distribution of characteristic wave heights for ten ocean stations

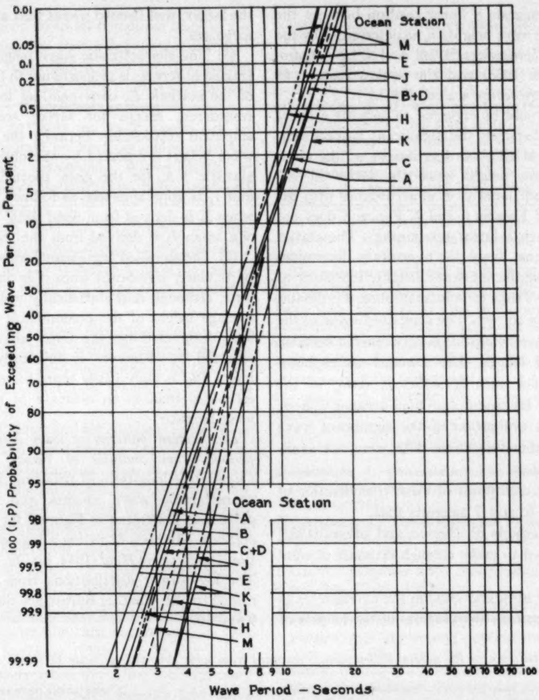

FIG. 10 – Distribution of characteristic wave periods for ten ocean stations

(e) The average value of the characteristic wave heights determined by the shipboard observers was tabulated.

(f) The Hydrographic Office computed a theoretical value of *E* on the basis of the distribution of wind velocities that generated the sea. This computation does not take account of swell that may have been present in the wave system. The method of *Pierson* and others [1955] was used, according to which *E* is proportional to the area under the power spectrum of the sea. These values are also given in Table 1.

In Figure 2, (a) is plotted against (e). In Figure 6, (c) is plotted against (f). In Figure 7, (a) is plotted against the square root of (f). In Figure 5, (d) is plotted against (e).

Figure 2 indicates that trained shipboard observers can, on the average, estimate the heights of the predominant waves reasonably well.

The value of *E* determined from the wind data should agree with the *E* obtained from the wave profiles provided the power-spectrum theory is valid, a narrow sea spectrum exists, swell is negligible, and the stereophotograph covered a representative area of the ocean. One may expect considerable deviations from these assumptions; for example, the sea surface profiles sometimes indicate considerable deviation from a narrow spectrum as well as the presence of swell. Nevertheless, Figure 6 suggests a linear relationship between the *E*'s determined by two independent methods. It is concluded that the wind data may be used to determine the sea state, at least qualitatively.

Figure 7 suggests a linear relation between the characteristic wave heights *h*, as determined by the methods of *Darbyshire* [1956] and *U. S. Hydrographic Office* [1955] and the square root of *E*, except for very severe sea conditions.

Figure 5 would be expected to indicate a linear relationship between the significant wave height and the visual shipboard estimates of the characteristic wave height since the latter is presumably proportional to *E* in accordance with the indications of Figures 6 and 7. Figure 5 does not contradict such a linear relationship. The scatter of values is most likely due to errors in determination of the significant wave height, inasmuch as Figure 2 shows that the visual shipboard estimates are reasonably correct. The computed value of the significant wave height (*d*) is very much a function of the cutoff length. The *Unimak* stereophotographs did not furnish sufficient data, in the opinion of the Hydrographic Office oceanographers, to permit an evaluation of the significant wave height; and therefore these data were not available for the plots.

From an overall point of view, consideration of Figures 2, 5, 6, and 7 suggests that

(1) The methods of *Pierson* and others [1955] may be applied to make a rough estimate of wind waves.

(2) Trained observers can, on the average, make reasonably accurate observations of the heights of the larger, well-formed waves that are present in a given sea.

(3) The characteristic wave height reported by trained observers is proportional to the square root of the statistic *E*, corresponding to the sea state considered, except for severe sea states. The empirical relationship between the characteristic wave height *h* reported by the observers and the statistic $\sqrt{E}$, for the data plotted in Figures 6 and 7, is approximately as follows $h = 1.53\sqrt{E}$ when *E* is derived from wind data, and $h = 1.88\sqrt{E}$ when *E* is derived from the wave data.

(4) The so-called 'significant' wave height is not particularly significant since it is difficult to compute, although it is statistically well defined. The average height of the predominant wave heights, here designated by the term 'characteristic,' as reported by observers, is physically more meaningful and is more easily reproduced on repetitive estimates than is an estimate of the significant wave height.

Distribution patterns of wave heights and wave periods from analysis of visual observations—Cumulative long-term distribution patterns of the characteristic wave heights and periods were plotted as illustrated in Figure 8 for the ten ocean stations. Methods of fitting a log-normal distribution are given by *Hald* [1952, pp. 29, 34–35, 62–63]. The log-normal distributions from the data furnished by the Weather Bureau are shown in Figures 9 and 10.

TABLE 2 – *Statistics for log-normal distributions computed from wave observations made in North Atlantic Ocean*

Ocean station	Latitude North	Longitude West	Characteristic wave heights						Characteristic wave periods					
			Dates of observations						Periods of record					
			From	To	Number of observations	Median value of characteristic wave height	Mean value of logarithm of characteristic wave height[a]	Variance (σ^2) of logarithm of characteristic wave height[a]	From	To	Number of observations	Median value of characteristic wave period	Mean value of logarithm of characteristic wave period[a]	Variance (σ^2) of logarithm of characteristic wave period[a]
						ft						sec		
A	62°00′	33°00′	Jan. 49	June 54	12,891	6.34	1.847	0.4524	Jan. 49	June 54	12,342	6.30	1.840	0.0935
B	56 39	51 00	Jan. 49	Dec. 54	15,547	6.59	1.886	0.4434	Jan. 49	June 55	16,060	6.40	1.857	0.0748
C	52 45	35 30	Jan. 49	Dec. 54	16,857	6.75	1.910	0.3763	Jan. 49	June 55	17,471	6.48	1.869	0.0873
D	44 00	41 00	Jan. 49	Dec. 54	16,804	6.26	1.834	0.3843	Jan. 49	June 55	17,310	6.24	1.831	0.0800
E	35 00	48 00	Jan. 49	Dec. 54	16,777	4.56	1.516	0.3765	Jan. 49	June 55	16,896	5.86	1.768	0.0939
H	36 00	70 00	Jan. 49	June 54	14,607	5.08	1.625	0.4237	May 49	June 54	13,647	5.92	1.779	0.0643
I	61 00	15 20	Jan. 47	June 53	11,274	7.36	1.996	0.3747	Jan. 49 Jan. 53	Dec. 51 Dec. 54	12,142	7.02	1.948	0.0546
J	52 30	20 00	Jan. 47	June 53	12,016	7.40	2.002	0.3863	Jan. 49 Jan. 53	Dec. 51 Dec. 54	11,593	7.29	1.986	0.0423
K	45 00	16 00	Jan. 49	Dec. 53	11,182	6.20	1.824	0.3033	June 49	Dec. 53	11,906	8.30	2.117	0.0548
M	66 00	02 00	Jan. 49	Dec. 53	14,324	4.99	1.608	0.2344	Jan. 49	Dec. 53	14,188	6.99	1.946	0.0676

Note: The statistical computations are based on truncated data. The truncation point is 2.5 ft for wave heights and 5 sec for wave periods.

[a] Logarithms are to the base *e*.

The rather good fit of all computed lines to the plotted data suggests that a log-normal distribution is a good approximation to the distribution pattern of characteristic wave heights and periods for values above the truncation point.

Distribution patterns for wave length can be derived from the data for wave periods by applying an approximate conversion: Wave length = constant × (wave period)^2. For fully developed waves the constant is 3.4.

It is apparent that the distribution of wave lengths will be log-normal if that for the periods is log-normal, since the conversion involves only a change in mean value and slope from the distribution of the periods.

In Table 2 mean values and variances are given for the wave height and period data reported from each ocean station. Also the latitudes, longtitudes, and observation periods over which the data were collected are shown.

Summary—Frequency distribution patterns of wave heights and wave periods may be approximated by a one-parameter type of distribution function when the environmental conditions are steady, whereas they will tend to follow the two-parameter logarithmically normal distribution when the environmental conditions are allowed to vary over a wide range. It should be emphasized that the log-normal distribution illustrated in Figure 8 is influenced much more by the usual sea conditions than by the rare occurrences of very high or very low seas. Thus one should expect greater deviations from the fitted line for very small and very large wave heights and wave periods than for those heights and periods which occur more frequently. It is concluded that the long-term distributions of wave height and wave period may be approximated by the log-normal distribution.

Reasonably accurate visual estimates of wave height can be obtained from trained observers, provided a number of independent estimates are averaged. A single estimate may be considerably in error.

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The opinions or assertions in this paper are the private ones of the authors and are not to be construed as official or reflecting the views of the Navy Department.

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Yield of Sediment in Relation to Mean Annual Precipitation

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Abstract—Effective mean annual precipitation is related to sediment yield from drainage basins throughout the climatic regions of the United States. Sediment yield is a maximum at about 10 to 14 inches of precipitation, decreasing sharply on both sides of this maximum, in one case owing to a deficiency of runoff and in the other to increased density of vegetation. Data are presented illustrating the increase in bulk density of vegetation with increased annual precipitation and the relation of relative erosion to vegetative density.

It is suggested that the effect of a climatic change on sediment yield depends not only upon direction of climate change, but also on the climate before the change. Sediment concentration in runoff is shown to increase with decreased annual precipitation, suggesting further that a decrease in precipitation will cause stream channel aggradation.

Introduction—The yield of sediment from a drainage basin is a complex process responding to all the variations that exist in precipitation, soils, vegetation, runoff, and land use. This study is aimed only toward a discernment of the gross variations in sediment yield that are associated with climate as defined by the annual precipitation. Such a study may contribute to an understanding of the effects of climatic change on erosion and of the regional variations in sediment yield. Data on sediment yields are now available in sufficient number for this kind of study, although still quite deficient in geographic coverage. Two major sources of sediment data exist. Records collected at about 170 gaging stations of the U. S. Geological Survey, where sediment transported by streams is measured, is one source of data; whereas, the other source of data is provided by the surveys of sediment trapped by reservoirs. Both kinds of data are used in this study.

Precipitation data—Precipitation is used as the dominant climatic factor in the study of sediment yield, because it affects vegetation and runoff. However, the effectiveness of a given amount of annual precipitation is not everywhere the same. Variations in temperature, rainfall intensity, number of storms, and seasonal and areal distribution of precipitation can also affect the yield of sediment. For example, *Leopold* [1951] in an analysis of rainfall variation in New Mexico, found that despite the absence of any trend in annual rainfall, changes in the number of storms produced a significant influence upon erosion. Although analyses of these effects are beyond the scope of this study, the effect of temperature, which controls the loss of water by evapotranspiration, can be readily taken into account. As is well known, the greater the temperature, the greater are the evapotranspiration demands upon soil moisture; hence, less moisture remains for runoff. More precipitation is required for a given amount of runoff in a warm climate than in a cool climate. Therefore, instead of using actual figures of annual precipitation, it is preferable to use figures of precipitation adjusted for the effect of annual temperature. However, in lieu of carrying out these extended computations, it appears possible to use the data on annual runoff which already reflect the influence of temperature. Annual runoff data are available for all the gaging station records and for most of the reservoir records. Because of the well-established relationships between annual precipitation and runoff, it is readily possible to estimate precipitation from the runoff figures.

We shall define effective precipitation as the amount of precipitation required to produce the known amount of runoff. Figure 1 shows a relationship between precipitation and runoff based on data given in Geological Survey Circular 52 [*Langbein*, 1949]. This graph has been used to convert known values of annual runoff to effective precipitation, based on a reference temperature of 50°F. In a warm climate, with temperature greater than 50°, the precipitation so estimated would be less than the actual amount of precipitation; in a cool climate, the effective precipitation so estimated would be more than the actual amount. This is the desired relationship.

Sediment-station data—In recent years a number of records of sediment yield, as measured at sediment-gaging stations, have become available. Annual loads were computed for about 100 stations giving preference to the smaller drainage areas in any region. All parts of the country,

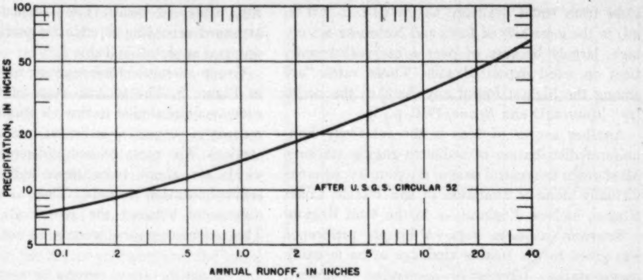

FIG. 1 – Relation between annual precipitation and runoff for a mean temperature of 50° F

where sediment records are collected, are represented.

The annual sediment loads were first arranged according to effective precipitation. They were next assembled into the class groups shown in Table 1, and the arithmetic averages were then computed for each group. Within any group the loads may vary tenfold, reflecting geologic and topographic factors not considered in this study. Each group mean is subject to a standard deviation of about 30 pct. The group averages are plotted in Figure 2. The curve shown was fitted to the data, subject to the condition (1) that it did not depart more than one standard deviation (30 pct) from any of the plotted group means, and (2) that it show zero yield for zero precipitation.

There is considerable opportunity for bias in the figures for load, because the relatively few records prohibit any high degree of selectivity. Few of the rivers drain areas in their primeval environment and moreover, land use can greatly affect the sediment yield. Farming, grazing, road construction, and channelization tend to increase sediment yield; reservoirs impound and, therefore, delay the movement of sediment. If these effects are uniform countrywide, then the overall results might be free of bias in the statistical sense, even though the absolute magnitudes may not be representative of primeval conditions. However, there is considerable variation, particularly with respect to intensity of agricultural operations, which perhaps are most intensive in the midcontinent region. The effects of various kinds of land use upon erosion vary with climate, physiography, soil type, and original vegetation. One surmises that the effect of cultivation is greater in the humid region, where effective precipitation is more than about 30 inches, because of the great contrast between original forest cover and tillage. The erosive reaction of some soil types to cultivation is evident for some small drainage basins in the humid region, which have sediment yields that approach or exceed those usual even in the arid country and are far above those to be expected within their particular range of annual precipitation. For example, sediment

TABLE 1 – *Group averages for data at sediment stations*

Range in effective precipitation	Number of records in each group	Average effective precipitation	Average yield
inch		inch	tons/sq mi
Less than 10	9	8	670
10 to 15	17	12.5	780
15 to 20	18	17.5	550
20 to 30	20	24	550
30 to 40	15	35	400
40 to 60	15	50	220

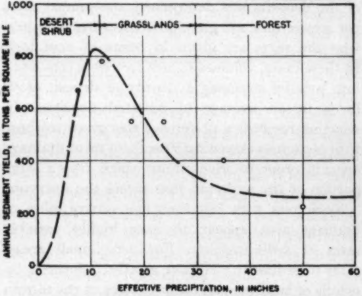

FIG. 2 – Climatic variation of yield of sediment as determined from records at sediment stations

yield from small drainage basins (0.1 to 1.0 sq mi) in the loess hills of Iowa and Nebraska is very high, largely because of poor conservation practices on wind deposited soils. These rates "are among the highest found anywhere in the country" [*Gottschalk* and *Brune*, 1950, p. 5].

Another source of bias is the relatively nonuniform distribution of sediment-gaging stations. Most are in the central part of the country, whereas virtually none is available in the Pacific Coast Region, in New England, or in the Gulf Region.

Reservoir sediment data—Although preference was given to the smaller drainage areas in using gaging-station records of suspended sediment, opportunities for choice in this regard were severely limited. Fortunately, surveys of sedimentation in reservoirs are more numerous, so that there was opportunity to be more selective in choosing reservoirs below small drainage areas, which on that account were presumed to be more indicative of sediment yield nearer the source. Data on reservoir sedimentation were compiled by the *Federal Inter-Agency River Basin Committee* [1953]. Rates of sedimentation were obtained from surveys of sediment accumulation, expressed as an annual rate in acre feet or tons per square mile of drainage area. For those reservoirs where the bulk density of the deposits was determined, the annual rates per square mile are given in terms of tons, otherwise the rates are given in terms of acre feet. In these cases, volumes in acre feet were converted into tons by assuming a density of deposit of 60 lb/cu ft, an average of reported densities. In selecting reservoirs, preference was given to those with capacities exceeding 50 ac ft/sq mi of drainage area, in order to select those which trap a large portion of the sediment that enters the reservoir.

Reservoirs with less than five square miles of drainage area appear to have highly variable rates of sedimentation. For very small areas, rates of sediment yield are greatly influenced by details of land use and local features of the terrain [*Brown*, 1950]. For this reason, reservoirs having drainage areas between 10 and 50 sq mi were used. Because no reservoirs in desert areas were listed in the Inter-Agency compilation, data for desert reservoirs were obtained from unpublished records collected by the U. S. Geological Survey. However, because these reservoirs were on drainage areas of ten square miles or less, rates of sediment yield for these desert reservoirs were adjusted downward to obtain equivalent rates from drainage areas of 30 sq mi, according to the 0.15 power rule explained below. The sediment data were arranged according to effective precipitation and grouped as shown in Table 2.

Group averages of the reservoir data are plotted in Figure 3. The general shape of the resulting curve is quite similar to the one obtained from the records of suspended sediment measured at river stations. The most evident difference is that the yields are about twice those indicated by the sediment-station records. There are significant differences between the two kinds of records. The sediment-station records do not include bed

TABLE 2. – *Group averages for reservoir data*

Range in effective precipitation	Number of reservoirs in each group	Average effective precipitation	Average yield	Remarks
inch		inch	tons/ sq mi	
8–9	31	8.5	1400	15 reservoirs in San Rafael Swell, Utah, and 16 in Badger Wash, Colo.
10	38	10	1180	26 reservoirs in Twenty-mile Creek basin, Wyo., 7 in Cornfield Wash, N. Mex., and 5 general.
11	12	11	1500	General
14–25	18	19	1130	General
25–30	10	27.5	1430	General, including debris basins in Southern Calif. considered as one observation.
30–38	20	35.5	790	General
38–40	11	39	560	General
40–55	18	45	470	General
55–100	5	73	440	General

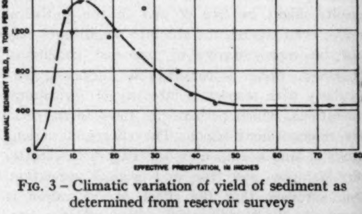

FIG. 3 – Climatic variation of yield of sediment as determined from reservoir surveys

load, which, being the coarser fraction of the load, is trapped by a reservoir. The effects are variable depending on relative amounts of bed and suspended loads at gaging stations and on the trap efficiency of the reservoirs. Moreover, reservoirs are generally built in terrain that offers favorable sites, which means drainage basins with steep slopes and hence higher rates of net erosion. However, in the comparison made here most of the difference is probably due to the effect of size of drainage area. Several studies have shown that sediment yields decrease with increased drainage area, reflecting the flatter gradients and the lesser probability that an intense storm will cover the entire drainage basin. Assuming that the graphs shown by *Brune* [1948] are correct for this effect, rates of sediment yield are inversely proportional to the 0.15 power of the drainage area. Noting that the drainage areas used for Figure 2 average about 1500 sq mi and those for Figure 3 about 30 sq mi, the sediment yields for reservoir data should average about $(1500/30)^{0.15}$, or 1.8 times that for the sediment-station data. This correction applied to the reservoir data would very nearly account for most of the difference between the curves of Figures 2 and 3.

Figures 2 and 3 appear to show a maximum sediment yield at about 12 inches annual effective precipitation, receding to a uniform yield from areas with more than 40 inches effective precipitation. The lack of data for climates with less than 5 inches of annual precipitation makes it difficult to determine the point of maximum yield with accuracy. Available data indicate, however, that it is at about 12 inches or less.

In a similar study of erosion rates and annual precipitation for large rivers of the world (Fig. 4), *Fournier* [1949] notes that the drainage basins are located on a parabolic curve in relation to their climatic character. For example, the upper limb of the parabola (greater than 43 inches) is formed by rivers typical of a monsoon climate: Ganges, Fleuve Rouge (Hung Ho), Yangtze, and some basins of southeastern United States; the middle segment of the curve between 24 and 43 inches of rainfall is formed by drainage systems located in regions with essentially equally distributed annual rainfall, as the Atlantic coastal rivers of the northeastern United States; the lower limb of the curve below 24 inches is formed by rivers draining regions of the more continental steppe or semiarid climates: Vaal, Indus, Rio Grande, Hwang-Ho, Tigris, and Colorado. Fournier concluded that the regions of maximum erosion are those in which monthly rainfall varies greatly, the monsoon and steppe climates.

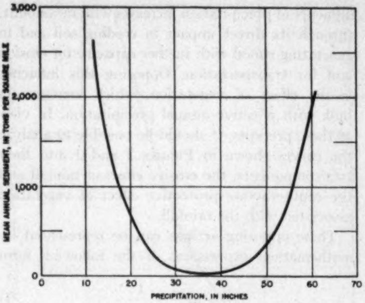

FIG. 4 – Relation of sediment yield to precipitation [after *Fournier*, 1949]

The midpart of his curve shows an annual yield of only five to seven tons per square mile which Fournier attributes to basins in which rainfall is uniform throughout the year such as those in the northeastern United States. These figures are much below that indicated by the few available records in that region which range from a minimum of about 40 tons/sq mi for Scantic River in Connecticut to 370 tons/sq mi for Lehigh River in Pennsylvania.

The lower limb of Fournier's curve terminates at a precipitation of about 12 inches, reaching an annual yield of about 2500 tons/sq mi. Although rates as high and even higher occur in many areas in the arid country, the figure of 2500 tons/year seems somewhat high as an average. The upward trend cannot continue if there is zero sediment yield (in rivers) for zero precipitation; the curve seemingly must reverse its upward trend and swing downward towards the origin.

The upper limb of Fournier's curve (above 43 inches precipitation) shows sharply increasing sediment yield with increasing precipitation, a trend that is not evident in Figures 2 and 3. However, it is possible that additional information in such areas of great rainfall as northern California and the Pacific Northwest may introduce an increasing trend in this part of those graphs.

Analysis of the climatic variation in sediment yield—The variation in sediment yield with climate can be explained by the operation of two factors each related to precipitation. The erosive influence of precipitation increases with its amount, through its direct impact in eroding soil and in generating runoff with further capacity for erosion and for transportation. Opposing this influence is the effect of vegetation, which increases in bulk with effective annual precipitation. In view of these precepts, it should be possible to analyze the curves shown in Figures 2 and 3 into their two components, the erosive effect of rainfall and the counteracting protective effect of vegetation associated with the rainfall.

These opposing actions can be represented by mathematical expressions of the following form

$$S = aP^{m} \frac{1}{1 + bP^{n}} \tag{1}$$

in which S is annual load in tons per square mile, P is effective annual precipitation, m and n are exponents, and a and b are coefficients. The factor aP^{m} in the above equation describes the erosive action of rainfall in the absence of vegetation. The die-away factor $1/(1 + bP^{n})$ represents the protective action of vegetation. The factor aP^{m} increases continuously with increase in precipitation, P, whereas the factor $1/(1 + bP^{n})$ is unity for zero precipitation, and decreases with increases in precipitation.

Eq. (1) can not be evaluated by the usual least-squares method. Hence it was evaluated by trial and error, graphical methods yielding the following approximate results.

$$S = \frac{10P^{2.3}}{1 + 0.0007P^{3.33}}$$

for sediment station data and

$$S = \frac{20P^{2.3}}{1 + 0.0007P^{3.33}}$$

for reservoir sediment data.

The factor $P^{2.3}$ describes the variation in sediment yield with constant cover. Analyses of measurements of rainfall, runoff, and soil loss made on small experimental plots operated by the Department of Agriculture [*Musgrave*, 1947], indicate that, other factors the same, erosion is proportional to the 1.75 power of the 30-minute rainfall intensity. However, it is rather difficult to draw a connection between the intensity of 30-minute precipitation and annual precipitation. Inspection of *Yarnell's* [1935] charts indicates one relationship exists in the eastern part of the country and another in the western areas. However, in both areas 30-minute intensities vary with annual rainfall to some power greater than unity. Hence, one can conclude that erosion will vary regionally to some power of the annual precipitation greater than 1.75.

The second factor, $1/(1 + 0.0007\ P^{3.33})$, equals $S/aP^{2.3}$. This function, as graphed in Figure 5, purports to isolate the variation in sediment yield caused by differing degrees of vegetative cover. This function varies as shown in Table 3.

There is a good deal of information on the relation between different vegetal covers and rates of erosion in a given climate. However, most of this information deals with cultivated lands and

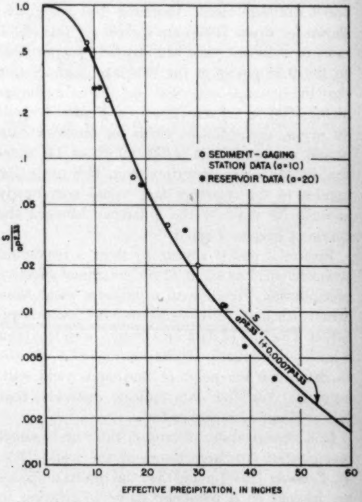

FIG. 5 – Decrease in relative sediment yield with increasing precipitation

TABLE 3 – *Variation in sediment yield associated with vegetative cover*

Effective precipitation	Vegetative cover[a]	$\frac{1}{1 + 0.0007\ P^{3.33}}$
inch		
7	Desert shrub	0.69
13	Desert shrub	0.23
20	Grassland	0.06
30	Grassland	0.017
40	Forest	0.006
50	Forest	0.003

[a] Associated with effective precipitation.

few of the vegetal data are in quantitative terms. *Musgrave* [1947] attempted a quantitative evaluation of relative erosion based on data collected at experimental watersheds in the Pacific Northwest. The results agree quite well with the results given in Table 3.

Cover	Relative erosion
Row crops or fallow	1.0 to 0.60
Small grains, grass hayland, crested wheat grass	0.05
Pasture, excellent condition, and forests	0.01 to 0.001

Formula (1) may be generalized as

$$S \propto R/V \qquad (2)$$

where R is annual runoff, and V is mass density of vegetation. In any given region the two factors operate separately; thus, sediment loads may vary with runoff depending on land use and vegetal conditions. For example, *Brune* [1948] shows that, for a given land condition in the Midwest, sediment yield increases with runoff, and that, for a given runoff, sediment yield varies enormously with percent of tilled land. The present study, however, treats of the broad climatic variation in which both runoff and vegetation are each uniquely related to effective precipitation.

With increasing precipitation, sediment yield varies as shown on Figures 2 and 3, but runoff increases as shown on Figure 1. The ratio between sediment yield and runoff is a measure of the concentration. This quantity is generally reported in parts per million (ppm) by weight and may be computed by dividing sediment yield in tons per square mile by runoff computed in tons per square mile. Figure 6 shows results of this computation for the data in Table 2. The concentration decreases sharply with increasing precipitation.

Annual precipitation, as indicated by the annual runoff, is used as the sole climatic measure. We have considered differences in precipitation intensity and its seasonal distribution only so far as these influences are reflected in the amount of annual runoff. For example, low precipitation regimes are characteristically more variable than those of humid regions [*Conrad*, 1946], and, indeed, the short-period excesses in intensity show up in the runoff. However, we repeat, as we wrote in our introduction, that although climatic influences on sediment are more complex, a good deal can be learned from consideration of the annual precipitation.

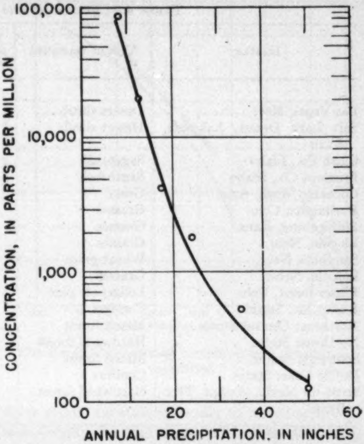

FIG. 6 – Variation of concentration with annual precipitation

Precipitation and vegetation—There can be no question of the highly significant effect of vegetation on erosion. For this reason, we have assembled information on climatic variation and vegetal bulk. The information on vegetal bulk contained in Table 4 was obtained mainly from published sources, ranging in reliability from carefully weighed quadrats to forest statistics and two estimates based on examination of photographs (for references, see Table 4). However, considering the more than 1000-fold variation in vegetal weight, as between desert shrubs to forests, great precision does not seem to be needed for the rough kind of study that seems possible at this time. Some of the data on vegetal weights were given directly in pounds per acre or equivalent. The forest data were obtained by dividing the reported cubic-foot volumes of saw-timber and pole-timber trees, given in millions of cubic feet for each state, by the respective forest area in acres. Unit weights of 45 lb/cu ft were used for hardwoods, 35 for soft woods, and 40 for mixed forests.

Table 4 also includes data on mean annual precipitation and temperature applicable to each case. The climatologic data were not usually given in the references cited and were obtained from U.S. Weather Bureau reports.

Figure 7 shows a plot of precipitation against

TABLE 4 – *Climatologic data and data on weight of vegetation*

Location	Type of vegetation	Mean annual precip.	Mean annual temp.	Weight of vegetation	Reference for vegetal bulk
		inch	°F	lb/ac	
Las Vegas, Nev.	Desert shrub	5	65	100	*McDougal* [1908, pl. 28]
Salt Lake Desert, Lakeside, Utah	Desert shrub	8	50	400	*McDougal* [1908, pl. 24]
Clark Co., Idaho	Sagebrush	12	40	891	*Blaisdell* [1953]
Fremont Co., Idaho	Sagebrush	12	40	1,273	*Blaisdell* [1953]
Coconino Wash, Ariz.	Grass	15	45	1,886	*Clements* [1922]
Burlington, Colo.	Grasses	17	52	2,251	*Weaver* [1923]
Phillipsburg, Kans.	Grasses	22	52	3,230	*Weaver* [1923]
Lincoln, Nebr.	Grasses	27	51	4,467	*Weaver* [1923]
Sandhills, Nebr.	Wheat grass	18	49	4,000	*Smith* [1895]
Lincoln, Nebr.	Grasses	27	51	6,224	*Kramer* and *Weaver* [1936]
Fraser forest, Colo.	Lodgepole pine	25	32	43,000	*Wilm* and *Dunford* [1948]
Rocky Mt. States	Conifers	28	38	54,000	*U. S. Forest Service* [1950]
Northeast Central States	Mixed forest	30	43	64,000	*U. S. Forest Service* [1950]
Northeast States	Hardwood forest	42	45	55,000	*U. S. Forest Service* [1950]
Southeast States	Mixed forest	51	60	48,000	*U. S. Forest Service* [1950]
Pacific Coast States	Conifers	64	47	150,000	*U. S. Forest Service* [1950]
Serro do Navio, Amapa Terr., Brazil	Hardwood forest	120		870,000	Field estimate by M. G. Wolman, 1956

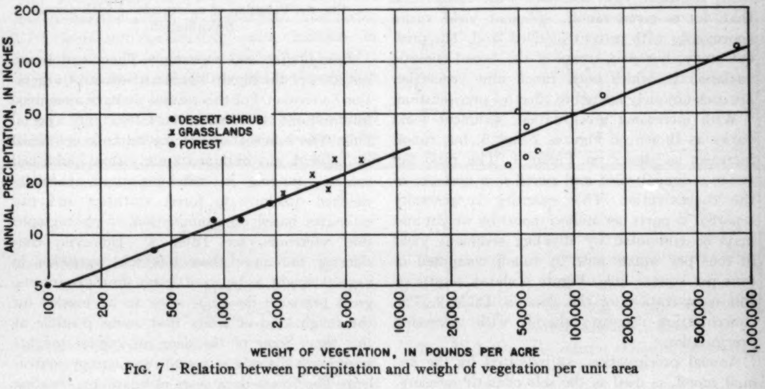

FIG. 7 – Relation between precipitation and weight of vegetation per unit area

vegetation weight. For the data available, the correlation seems quite high with a decided break between forest and nonforest types. The graph indicates that for equivalent rainfall, forests have about five times as much weight as grasses. With a longer life span, trees should understandably show greater total weight in place, although perhaps the annual growth (= annual decay for equilibrium) would be less than for grasses.

The seeming fact that desert shrubs are on the lower continuation of the line defined by the grasses seems anomalous. In arid and semi-arid regions the increase in vegetal bulk with rainfall rather simply reflects increasing opportunity for a greater number of plants, greater opportunity for each plant to reach maximum development for the species environment, and opportunity for growth of larger species. However, this does not explain the variation of forest bulk with rainfall greater than needed to satisfy optimum evapotranspiration demands for the climate. Forests are areas of water surplus in the climatic sense, yet vegetal density seems to vary with precipitation and temperature. Among the eastern states, for example, the vegetal bulk per unit area in Maine and North Carolina are about the same. The lesser annual precipitation in Maine appears to be compensated by a lesser temperature; whereas, in North Carolina higher annual precipitation is compensated by a higher temperature. The forested areas of Washington, Oregon, and California have about the same temperature; the forest densities seem to follow precipitation as follows:

State	Precipitation inch	Vegetation lb/ac
Washington	80	177,000
Oregon	60	158,000
California	53	120,000

The variation in unit weight shown in Figure 7 is made up of two components, one due to variation in weight among different communities of the same vegetation type, and that due to variation in weight among different types. The latter is very likely the dominant factor in the relationship on Figure 5. Beyond a certain limiting precipitation, say that for which precipitation is adequate to meet all evapotranspiration requirements, differences in vegetal bulk may reflect not so much growth factors as differences in plant types or associations. The heavy vegetal bulk in the Pacific Northwest, for example, may be the reflection of a difference in plant type rather than a direct effect of precipitation on growth.

We are considering here only gross relations, ignoring rather important variations that might be due to differences in species, topographic setting, or moisture conditions that might favor or discourage growth. For example, there are patches of timber in the valley bottoms, in the Great Plains, with weight densities far exceeding that of the grasslands. The data used to define this relationship are admittedly crude and subject to bias. The forest statistics, for example, generally exclude bark, leaves, flowers, fruit, and most branches. The ratio of these parts to the whole tree decreases with age. The existing data are for stands in various degrees of maturity, and most existing data exclude roots. The ratio of roots to aboveground growth is variable among different kinds of plants and may be a large source of error.

Then again, although one might conceive that the maximum amount of plant material should theoretically be correlative with climate, other factors such as aspect, depth, and nature of soil are of major influence. Ideally, vegetal densities should be studied locally to arrive at a normal density for the regional climate. However, this kind of study would be beyond the scope of this discussion. Only the evident fact that vegetal densities are so variable over the range of climates experienced in this country makes it at all possible to use the existing data.

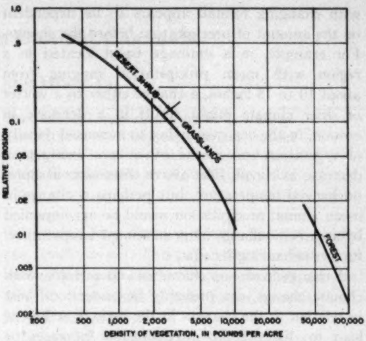

FIG. 8 – Relative erosion compared with density of vegetation

Interpreting the graph in Figure 5 as an indication of relative erosion associated with vegetation, as shown on Figure 7, the relationship shown on Figure 8 can be drawn. According to this graph, a relative change in vegetal density is effective on erosion throughout the climatic range, although the break between trees and grass suggests that per pound, grass is more effective in retarding erosion than trees.

Erosion and climate change—Examination of Figures 2 and 3 may be useful in visualizing not only variations in rates of net erosion between climatic zones in the United States but also the probable change in rates of erosion and stream activity during a climatic change.

Within the 0- to 12-inch precipitation zone an increase in annual rainfall would apparently be followed by an increase in erosion and vice versa; whereas, between about 12 to 45 inches of rainfall, erosion should decrease with increased precipitation. Above 45 inches of precipitation, erosion should remain about constant with increased precipitation, although Fournier's curve (Fig. 4) shows a marked increase in sediment yield above 43 inches of precipitation.

The direction of a change in sediment yield with changing rainfall appears to be dependent on the amount of precipitation before the change. For example, in a drainage basin located in a region with mean precipitation ranging from about 10 to 15 inches, a change either to a wetter or drier climate might result in a decrease in erosion, in the one case owing to increased density of vegetation and in the other case owing to a decrease in runoff. The above discussion assumes unchanged temperature, but perhaps a change in mean annual precipitation would be accompanied by an inverse change in mean annual temperature, further enhancing its effects.

A change in stream character and activity, with climate change, can probably be understood best in relation to the changes in the ratio of sediment load to discharge as precipitation increases or decreases. Referring to Figure 6, it is apparent that as annual precipitation decreases, the concentration of sediment per unit of runoff increases. This suggests quite strongly that, other factors being the same, the increasing sediment loads associated with increasing dryness will cause aggradation, in an amount depending on the magnitude of the climatic change. *Mackin* [1948, pp. 493–495] has summarized changes to be expected in stream activity with changes in load and discharge. In every case, an increase in load or decrease in discharge with constant load results in aggradation and vice versa.

The decrease in annual runoff with decreased precipitation will necessitate an adjustment of stream gradient and shape according to established principles [*Leopold* and *Maddock*, 1953], such that the width and depth of the channel should decrease and gradient increase. These changes are consistent with aggradation. Of course, an increase in precipitation might be expected to result in degradation as sediment concentration decreases. The increased discharge will result in an increase in channel width and depth and a decrease in gradient. Numerous exceptions to the above generalizations can be cited, especially when glaciation, deforestation, cultivation, or a change in base level become important.

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Secondary Currents in Straight Channels

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Abstract—The existence of straight uniform flows without secondary current is studied. It is shown that laminar flows of this kind can remain without secondary currents independent of cross section and velocity distribution. For turbulent flows it is shown that secondary flows will develop spontaneously if in any part of the section the expression for $\partial\xi/\partial t$ as given in Eq. (19) is not vanishing.

When the hydraulic engineer speaks of a flow channel he visualizes boundaries confining a flow which is predominantly one-directional. Such flows have been observed to possess a rotation or circulation around an axis parallel to the main flow velocity, transforming it into a helical or multihelical flow. These superimposed rotations are usually called secondary motion. Best known is the occurrence of such secondary currents in bends of pipes and open channels where they are explained by the difference of the centrifugal effects in flow lines of various flow velocities [*Goldstein*, 1938, pp. 84–87].

This explanation does not hold in a straight channel. Since secondary currents have been observed to develop in many straight channels, the authors of this paper felt the necessity of finding a new, and probably basically different explanation of these secondary currents. It is most interesting that such an explanation can be derived directly from the basic flow equations, the Navier-Stokes equations [*Lamb*, 1932, pp. 577–578].

The secondary motion in rivers is important in its effect on bed sediment. It provides for systematic cross motion of the sediment within the channel, concentrating it in some areas in the form of bars and removing it from other areas causing deep scour holes. More apparent to the observer is the concentration of drift wood and drifting ice into individual parts of the river surface. This last effect permits secondary currents to be easily recognized. Less known is the effect of secondary currents on the distribution of the suspended sediment. But even if this effect has not been studied systematically, one must expect its influence to be considerable because of the extremely large size of the effective mixing length.

The basic method of approach—It would be most direct and appropriate to establish the flow equations including secondary currents and to show from these general equations under which conditions such secondary currents have values different from zero. This direct approach has not yielded any results as yet. This paper describes instead an indirect method which tries to establish the conditions under which a flow free of secondary currents is not stable.

In order to eliminate the known effects of various accelerations of the main flow on the secondary currents, the following analysis is restricted to a straight, uniform flow. The generality of the results is not impaired if the x axis is assumed to have the direction of the main flow, while all cross sections are parallel to the yz plane.

The flow equations—Using *Lamb's* [1932, pp. 577–578] nomenclature the Navier-Stokes equations may be written in Cartesian coordinates for an incompressible fluid not affected by outside forces.

$$\frac{Du}{Dt} = -\frac{1}{\rho}\frac{\partial p}{\partial x} + \nu\nabla^2 u$$
$$\frac{Dv}{Dt} = -\frac{1}{\rho}\frac{\partial p}{\partial y} + \nu\nabla^2 v \tag{1}$$
$$\frac{Dw}{Dt} = -\frac{1}{\rho}\frac{\partial p}{\partial z} + \nu\nabla^2 w$$

Herein u, v, w are the velocity components in the direction of x, y, and z, respectively; p is the pressure, and ν the kinematic viscosity of the fluid. D/Dt is the total derivative moving with the fluid particle and $\nabla^2 = \partial^2/\partial x^2 + \partial^2/\partial y^2 + \partial^2/\partial z^2$, an operator. The corresponding continuity equation is

$$\partial u/\partial x + \partial v/\partial y + \partial w/\partial z = 0 \tag{2}$$

A more useful form of the equations for the purpose of this paper is obtained if the vorticity is introduced which is defined as a vector with the following three components, which can be expressed more concisely by using indices x, y, z, t to designate partial derivatives

$$\xi = \frac{\partial w}{\partial y} - \frac{\partial v}{\partial z} = w_y - v_z$$

$$\eta = \frac{\partial u}{\partial z} - \frac{\partial w}{\partial x} = u_z - w_x \qquad (3)$$

$$\zeta = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} = v_x - u_y$$

Each of these components represents a measure of the instantaneous speed of rotation in the fluid as measured by that of a unit area; ξ for instance, represents the x component of the rotation, as measured by the circulation around a unit square in the yz plane. *Lamb* [1932, pp. 577–578] shows that (1) may be rewritten

$$\frac{D\xi}{Dt} = \xi u_x + \eta u_y + \zeta u_z + \nu\nabla^2\xi$$

$$\frac{D\eta}{Dt} = \xi v_x + \eta v_y + \zeta v_z + \nu\nabla^2\eta \qquad (4)$$

$$\frac{D\zeta}{Dt} = \xi w_x + \eta w_y + \zeta w_z + \nu\nabla^2\zeta$$

with a 'continuity equation' for vorticity applicable in the form

$$\xi_x + \eta_y + \zeta_z = 0 \qquad (5)$$

The correctness of the latter can easily be demonstrated by introducing the definition of the vorticity (3) into (5), and by cancelling identical terms with opposite sign.

The vorticity components as defined by (3) represent the flow circulation around a unit area element at right angles to the particular vorticity component. So is for instance ξ the flow circulation around the unit area in a plane defined by $x =$ const. If ξ is integrated over any arbitrary area of the same x plane, the integral is equal to the flow circulation around the area, or, according to our definition, equal to the secondary current in this area. It is easily visualized from this that the patterns of secondary currents are given in any cross section by continuous areas in which the vorticity ξ has the same sign.

Following the proposed plan, a uniform flow is assumed (characterized by the fact that all partial derivatives of time-average values with respect to x become zero) and for which ξ is equal to zero at a given time. $D\xi/Dt$, or what is equivalent in a uniform flow $\partial\xi/\partial t$ is calculated for this flow. If $D\xi/Dt$ equals zero this flow is stable indicating the possibility of a stable flow free of secondary currents; if it has a finite value this constitutes proof that such a straight uniform flow without secondary currents is impossible.

In order to make the investigation more general a turbulent flow is assumed in which all velocity and vorticity components can be divided into an average value, designated by an overscore, and a deviation from this average, designated by prime, such that, for instance

$$u = \bar{u} + u' \qquad (6)$$

It is clear that the time average of any such deviation becomes equal to zero by definition. The usual assumption is made that not only the time-average of the deviations themselves but also those of the derivatives of the deviations disappear. Now, the first of (4) is transformed in the described way and averaged with respect to time. Note that the first and last term of the right side disappear for $\xi = 0$ because of the previous assumption and $\bar{\xi}' = 0$ as deviation.

$$D\xi/Dt = \bar{\eta}\bar{u}_y + \bar{\zeta}\bar{u}_z + \overline{\xi' u'_x} + \overline{\eta' u'_y} + \overline{\zeta' u'_z} \qquad (7)$$

Using (3), the right side of (7) is rewritten as follows

$$\begin{aligned} D\xi/Dt = {} & \bar{u}_z\,\bar{u}_y - \bar{w}_x\,\bar{u}_y + \bar{v}_x\,\bar{u}_z - \bar{u}_y\,\bar{u}_z + \overline{w'_y u'_x} \\ & - \overline{v'_z u'_x} + \overline{u'_z u'_y} - \overline{w'_x u'_y} + \overline{v'_x u'_z} - \overline{u'_y u'_z} \end{aligned} \qquad (8)$$

In (8) the first term of the right side cancels against the fourth and the seventh against the last. The values w_x and $\bar{v}_x$ are zero according to the assumption of uniform flow leaving only

$$D\xi/Dt = -\overline{w'_x u'_y} + \overline{v'_x u'_z} + \overline{w'_y u'_x} - \overline{v'_z u'_x} \qquad (9)$$

The expression $\overline{(w' u'_y)}_x = 0$ is a derivative with respect to x of an average value. Therefore

$$\overline{w'_x u'_y} = -\overline{w' u'_{xy}} = \overline{w' v'_{yy}} + \overline{w' w'_{yz}} \qquad (10)$$

using the continuity equation (2). Similarly

$$\overline{v'_x u'_z} = \overline{v' w'_{zz}} + \overline{v' v'_{yz}} \qquad (11)$$

Again, using the continuity equation, one can write

$$\begin{aligned} \overline{w'_y u'_x} &= -\overline{w'_y v'_y} - \overline{w'_y w'_z} \\ \overline{v'_z u'_x} &= -\overline{v'_z v'_y} - \overline{v'_z w'_z} \end{aligned} \qquad (12)$$

Introducing (10), (11), and (12) into (9)

$$\begin{aligned} D\xi/Dt = {} & -\overline{w' v'_{yy}} - \overline{w' w'_{yz}} + \overline{v' w'_{zz}} + \overline{v' v'_{yz}} \\ & -\overline{w'_y v'_y} - \overline{w'_y w'_z} + \overline{v'_z v'_y} + \overline{v'_z w'_z} \end{aligned} \qquad (13)$$

The left side of (13) can be rewritten as follows

$$\begin{aligned} D\xi/Dt = {} & \bar{\xi}_t + \overline{\xi'_t} + \overline{u\xi_x} + \overline{u'\xi'_x} + \overline{v\xi_y} \\ & + \overline{v'\xi'_y} + \overline{w\xi_z} + \overline{w'\xi'_z} \end{aligned} \qquad (14)$$

In (14) the second term by definition, and the third, fifth, and seventh disappear, since ξ is assumed to have zero average at the time under consideration. Of the remaining terms, 4, 6, and 8 are expanded using (3).

$$D\xi/Dt = \bar{\xi}_t + \overline{u'w'_{xy}} - \overline{u'v'_{xz}} + \overline{v'w'_{yy}} - \overline{v'v'_{yz}} + \overline{w'w'_{yz}} - \overline{w'v'_{zz}} \quad (15)$$

The first two terms containing u can be transformed again as follows

$$(\overline{u'w'_y})_x = 0 = \overline{u'_xw'_y} + \overline{u'w'_{xy}} = -\overline{v'_yw'_y} - \overline{w'_zw'_y} + \overline{u'w'_{xy}} \quad (16)$$

or

$$\left.\begin{aligned} \overline{u'w'_{xy}} &= \overline{v'_yw'_y} + \overline{w'_zw'_y} \\ \text{and similarly} \qquad & \\ \overline{u'v'_{xz}} &= \overline{w'_zv'_z} + \overline{v'_zv'_y} \end{aligned}\right\} \quad (17)$$

Introducing (17) into (15) and combining it with (13), one obtains

$$\xi_t = -\overline{w'v'_{yy}} - \overline{w'w'_{yz}} + \overline{v'w'_{zz}} + \overline{v'v'_{yz}} - \overline{w'_yv'_y} - \overline{w'_yw'_z} + \overline{v'_zv'_y} + \overline{v'_zw'_z} - \overline{v'_yw'_y} - \overline{w'_zw'_y} + \overline{w'_zv'_z} + \overline{v'_zv'_y} - \overline{v'w'_{yy}} - \overline{w'w'_{yz}} + \overline{v'v'_{yz}} + \overline{w'v'_{zz}} \quad (18)$$

These sixteen terms can be combined as follows

$$\bar{\xi}_t = \frac{\partial^2}{\partial y \partial z}(\overline{v'^2} - \overline{w'^2}) + \frac{\partial^2}{\partial z^2}(\overline{v'w'}) - \frac{\partial^2}{\partial y^2}(\overline{v'w'}) \quad (19)$$

Eq. (19) represents the main result of this study and needs some discussion. The value $\overline{v'^2}$ for instance can be interpreted as pressure fluctuation in the y direction due to turbulence, divided by the constant density of the fluid. Figure 1 shows a pressure diagram on the unit area in the zx plane, $\overline{v'^2}$ is the average pressure, while the marked area gives the deviation from uniform distribution over the area as expressed by the change of $\overline{v'^2}$ in direction z. If the distribution of v'^2 is the same on the left hand and on the right side of the unit square of Figure 1, the unit body is still in equilibrium. If the two distributions are unequal, however, as described by a change of the distribution in direction y, a moment is applied to the body, causing it to change its speed of rotation around the x direction, or in other words, the unit rotation ξ is changed. The same argument applies to the $\overline{w'^2}$ term.

The effect of the two last terms is quite different. The average $\overline{v'w'}$ is well known as a Reynolds stress acting on xy or xz planes in direction y or z, respectively. A first derivative of this stress with respect to z or y, respectively, indicates the change of the shear stress through the unit body of fluid, the resulting force on this body. If a second derivative is found to be in the same direction, the unequal distribution of this force is obtained, which again causes the unit body to change its speed of rotation around the x direction, the rotation ξ.

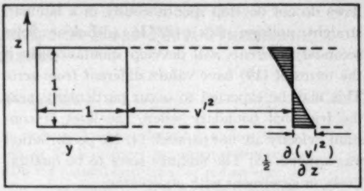

FIG. 1 – Visualization of the term $\frac{\partial(\overline{v'^2})}{\partial z}$

Next the question arises in which flows the various terms of (19) do not vanish. In isotropic turbulence or even near-isotropic turbulence such as near the center of a pipe flow $\overline{v'^2}$ and $\overline{w'^2}$ are equal in magnitude such that the first part does not contribute to the change of ξ. But also the Reynolds stresses are zero in isotropic turbulence and its second derivatives are vanishing everywhere the shear distribution is linear, such as in two dimensional flow or in a circular pipe. It is more difficult to specify where the terms of (19) do not vanish. The difference $(\overline{v'^2} - \overline{w'^2})$ is different from zero mainly near a frictional boundary. The derivative does not disappear in one of the two directions y and z if the flow pattern changes as one follows the boundary in the cross section. This fact can best be characterized by lines of constant velocity in the cross section which are parallel neither to the boundary nor among themselves. The shear terms will contribute to the change of ξ whenever the shear distribution is nonlinear. This again may be expected to occur where the lines of constant velocity are not parallel.

Summary and conclusions—The following conclusions are drawn: (1) The stability of straight uniform flows without secondary currents was studied by determining the change with time of the vorticity in the direction of the main flow. (2) No terms containing average velocity components cause such a change, indicating that secondary flows do not develop spontaneously in a laminar, straight uniform flow. (3) In turbulent flows secondary currents will develop spontaneously if the terms of (19) have values different from zero. This may be expected to occur particularly near the frictional boundary where the lines of constant velocity are not parallel. (4) No perturbation was applied. (5) The findings seem to be qualitatively in agreement with observation.

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Conductivity and Length Relationships in Heat-Flow Transducer Performance

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Abstract—In recent years many investigators have used thermoelectric heat-flow transducers to measure heat conduction in natural soil. If the transducer has thermal properties different from those of the soil it will interfere with the natural heat transfer and an error in measurement will occur. An analysis of the error for a transducer placed in an infinite medium in steady-state conditions is made in terms of two non-dimensional parameters: (1) the ratio of transducer conductivity to soil conductivity, and (2) the ratio of transducer thickness to transducer width. An exponential relationship is postulated on the basis of physical considerations and is verified by the results of an electrical analogy experiment for a square transducer having a thickness-width ratio of 0.125 for conductivity ratios from about 0.1 to 2.2. An error of −70 pct was found for a conductivity ratio of 0.1 and an error of +5 pct for a conductivity ratio of 2.2. The results are used to estimate error in measurements made during the Great Plains Turbulence Field Program.

Introduction—A heat-flow transducer, or heat-flow meter, is a device for the direct measurement of heat transfer in one dimension. It usually consists of a thin sheet or plate of insulating material fitted with thermocouple junctions. The latter are arranged so that they form a thermopile having an output proportional to the temperature gradient across the plate. In steady conditions, therefore, the thermopile output is a direct measure of heat conduction through the plate.

In studying evaporation from natural soil, snow, or vegetation-covered surfaces by means of the energy balance a heat-flow transducer may be used to determine heat conduction in the soil. Use of such a device in soil was first reported by *Falkenberg* [1930] who attempted to use a circular Woods metal plate by placing it directly on the soil surface. *Dunkle* [1940] described an improved 'heat meter' made of Bakelite and having about 480 thermocouple junctions placed in a plate one-eighth inch thick and four and one-half inches square. He suggested that it be used in soil as well as in other media to measure heat transfer. *Deacon* [1950] described two transducers for soil heat-transfer measurements. He showed how they could be used by placing them one centimeter or less beneath the soil surface. Since that time transducers of the type described by Dunkle have been used by many investigators. Reference may be made, for example, to *Brooks* and *Kelly* [1951], *Gerhardt* [1957], *Portman* [1957], and *Rhoades* [1957].

Heat-flow transducers have been used for many other purposes, particularly for measuring heat transfer in building walls. They might be used, as well, in dams and other hydrological structures wherever it is desired to measure heat transfer.

Although the use of a transducer is perhaps the simplest and most convenient method of measuring soil heat transfer it is not always without difficulty. An important problem arises from the fact that the transducer acts as a barrier to the movement of soil moisture. Transducers made by Gier and Dunkle for use in soil had a rectangular grid of 25 holes, $\frac{3}{16}$ inches in diameter, equally spaced over the $4\frac{1}{2} \times 4\frac{1}{2}$ inch plate. The holes permitted vertical movement of water and water vapor. It is probable that, for a solid transducer, the barrier effect would decrease as the horizontal dimension of the plate is decreased. Nevertheless, transducers have been found to give relatively accurate information for energy-balance studies in moderately dry soil and for heat transfer at depths where vertical movement of water is negligible.

Another difficulty arises if the thermal properties of the transducer are significantly different from those of the soil. For steady-state conditions, only thermal conductivity and length relationships enter the problem. If the conductivity of the transducer is not equal to that of the soil, the soil heat-flow pattern will be distorted. For a given conductivity inequality the amount of distortion will depend on the width and the thickness of the transducer and the depth of placement in the soil. If there is distortion, the heat flow through the transducer will not equal that in the undisturbed soil for an equal area. It is the purpose of this analysis to determine the effect of conductivity and length relationships in the performance of heat-flow transducers.

Theoretical considerations—The following discussion and conclusions apply to a square transducer in steady-state conditions. It is assumed, moreover, that if the two conductivities are equal, no discontinuity of conductivity exists at the soil-transducer interfaces, and if they are not equal an abrupt discontinuity exists, that is, there is no 'contact resistance.'

With these assumptions it can be physically reasoned that the ratio X of the transducer heat flow q_t to the undisturbed soil heat flow q_s will be determined by the soil conductivity k_s, the transducer conductivity k_t, the transducer width (= length) W, the transducer thickness L, and the depth D of transducer placement. Thus

$$X = q_t/q_s = \phi_1(k_t, k_s, W, L, D) \quad (1)$$

in which ϕ_1 is an unknown function. By inspection it is seen that the five variables can be combined in three non-dimensional ratios for convenience of analysis, and (1) can be written

$$X = \phi_2(k_t/k_s, L/W, D/W) \quad (2)$$

It is apparent that if $k_t < k_s$ then $q_t < q_s$ and if $k_t > k_s$ then $q_t > q_s$. In the former case the transducer offers more resistance to heat flow than does an equal thickness of soil. There will be a tendency, consequently, for heat to flow around the transducer. In the latter case the opposite condition exists so that more heat tends to flow through the transducer than through an equal thickness of soil. Furthermore, an increase in L/W can be thought of as an increase in L holding W constant. Hence, it is obvious that the distortion, as indicated by the deviation of X from unity, will increase with an increase in thickness L. On the other hand, a decrease in L/W can be thought of as a decrease in L holding W constant, and it becomes clear that this would decrease the degree of distortion.

If it is assumed that at the soil surface there exists a uniform heat source or sink, uninfluenced by the nearness of the transducer, it can be reasoned that a decrease in depth will decrease any existing distortion, other factors being constant. A uniform source or sink at the surface implies that the flow lines there are parallel and vertical, that is, perpendicular to the surface. Distortion at the transducer implies that as the transducer is approached from the surface the flow lines tend either to concentrate toward the center of the transducer or to deflect away from it. It can be imagined that as the depth is decreased there can be less deflection, or less concentration, merely because more curvature in flow lines will be required to effect the same distortion. For $k_t < k_s$, as with the case for a wide transducer, resistance for heat to flow through the transducer would be less effective since an increase in curvature means an increase of the path to flow around the transducer. Similar, but converse, reasoning would explain the opposite situation.

The model of a uniform source or sink at the surface seems somewhat unrealistic, however. If a transducer for which $k_t/k_s \neq 1$ were very near the surface, the flow pattern distortion would alter the surface temperature and a uniform source or sink could no longer be assumed to exist. Actually, the energy transfers at the surface could then be expected to be different and the situation would be dependent on external conditions. It is difficult to estimate these effects in rendering the above model invalid.

Because of the last-mentioned difficulty and because a solution of the problem would have application without consideration of the dependency on depth it seems reasonable to consider the case for a transducer placed in an infinite medium for a first analysis. The equation to be solved then is

$$X = \phi_3(k_t/k_s, L/W) \quad (3)$$

Considerable insight on the problem may be gained by establishing the limits of X for various values of k_t/k_s for any L/W. The following inequalities establish the envelope of a family of curves for all values of L/W: For $k_t > k_s$, $q_t > q_s$, and $\Delta T/L < G$, $X > 1$ and $(\Delta T/L)/G < 1$, in which ΔT is the average temperature difference across the transducer and G the vertical temperature gradient in undisturbed soil. Since

$$X = \frac{k_t}{k_s}\frac{\Delta T/L}{G}, \qquad X < \frac{k_t}{k_s}$$

Conversely, for

$$k_t < k_s, \qquad X > k_t/k_s$$

The cross-hatched areas in Figure 1 show the regions in which the curves must lie for all values of L/W. Note that all curves must pass through the points $X = k_t/k_s = 0$ and $X = k_t/k_s = 1$.

The form of a curve within this envelope may be explored with the following reasoning.

From (3) and the defining relationships of q_t

and q_s

$$\frac{\Delta T/L}{G} = \phi_4(k_t/k_s, L/W) \tag{4}$$

and as $k_t \rightarrow 0$

$$\frac{\Delta T/L}{G} = \phi_4(0, L/W)$$

The latter function, $\phi_4(0, L/W)$, must equal or be greater than unity and it must approach unity as L/W approaches infinity. Since in reality L/W ratios for transducers are always smaller than, at most, 0.1, it may be established that $\phi_4(0, 0.1) = A/G > 1$. It follows, then, that

$$X = \frac{k_t \Delta T/L}{k_s G} < \frac{k_t A}{k_s G} \tag{5}$$

in which A has an undetermined value.

Similarly, for k_t approaching infinity

$$X = \phi_5(\infty, L/W) \geqq 1$$

and in this case as $L/W \rightarrow 0$, $X \rightarrow 1$, and as L/W approaches its maximum value 0.1

$$X = \phi_5(\infty, 0.1) = C \tag{6}$$

in which C has an undetermined value.

Hence the areas of Figure 1 are restricted by the above considerations to those indicated in Figure 2. The lines $X = (k_t/k_s)\ (A/G)$ and $X = C$ were arbitrarily placed.

The problem remains of finding the function ϕ_3 in (3) with the conditions that as

$$k_t/k_s \rightarrow 0, \qquad X \rightarrow 0$$

and as

$$k_t/k_s \rightarrow 1, \qquad X \rightarrow 1 \tag{7}$$

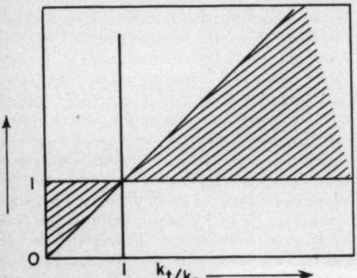

FIG. 1 – Flux ratio limits

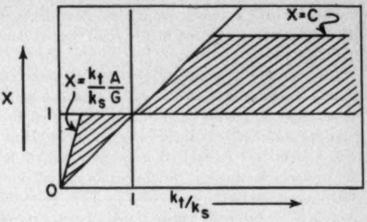

FIG. 2 – Restricted flux ratio limits

The two conditions immediately suggest that ϕ_3 is an exponential function. Hence, taking logarithms, one may write (3) as

$$\ln X = \phi_6(k_t/k_s, L/W) \tag{8}$$

or

$$\ln X = \sum_{n=0}^{\infty} (L/W)^n \psi_n(k_t/k_s)$$

with ψ representing another function. For values of L/W much less than one, powers of L/W may be neglected for a first approximation. Thus

$$\ln X \approx \psi_0(k_t/k_s) + L/W\psi_1(k_t/k_s)$$

but as

$$L/W \rightarrow 0$$

$$X \rightarrow 1$$

$$\ln X \rightarrow 0$$

$$\text{and} \quad \psi_0(k_t/k_s) \rightarrow 0$$

therefore

$$\ln X \approx L/W\psi_1(k_t/k_s) \tag{9}$$

or

$$X \approx e^{L/W\psi_1(k_t/k_s)}$$

From (7) it was found that the function could be expressed as in the following equation

$$X = e^{aL/W(1-k_s/k_t)} \tag{10}$$

in which a is assumed to be a constant greater than zero.

Experimental verification—An electrical analogy experiment was used in an attempt to verify the form of (10) and to evaluate a. The experiment consisted of submerging a model of a heat-flow transducer in a tank of water in which a uniform and steady alternating current potential was maintained. The electrical resistance of the model was varied and, in effect, the current flow through the model was compared to the undisturbed flow in the tank.

This method of verifying (10) was undertaken mainly because the necessary electrical equipment could be readily obtained on loan from the Department of Civil Engineering of Johns Hopkins University. It seemed admirably suited to the problem because of the geometrical and conductivity relationships involved. The analytic approach for the three dimensional case appeared to be particularly cumbersome without an electronic computer since lengthy approximation methods would be required. Furthermore, an analogy method with resistance networks did not seem to offer a very direct approach.

The experimental technique and the electrical system employed have been described by *Li* and others [1954] who used the same equipment to solve a water-flow problem. The physical system consisted of three components: (1) an alternating current source of about 800 c/s, (2) a combined potentiometer and Wheatstone bridge arrangement with earphones and probe, and (3) the electrolytic tank, its electrodes and the model.

Alternating current is required for an experiment of this type to avoid deposition of the electrolyte at the electrodes. An audio frequency is employed so that the experimenter can use earphones instead of a galvanometer, enabling him to locate equipotential lines in the electrical field by merely listening for a minimum tone. The potentiometer circuit was used in this case to measure the average potential difference between the two sides of the transducer model and to determine the potential drop over an equal interval in an undisturbed portion of the tank. The Wheatstone bridge served to evaluate the total resistance of the model and the resistance of the water in the tank.

The potentiometer and bridge were so arranged that a single switch changed the whole system from one for measuring resistance to one for measuring potential, or *vice versa*. The audio frequency source and the earphones and probe were used for both systems. Since the circuit diagrams have been published [*Li* and others, 1954, pp. 807, 808] the electrical system will not be further discussed.

An ordinary rectangular glass aquarium was obtained for the electrolytic tank. It was approximately 25 × 50 cm, and 30 cm deep. The two ends were fitted with flat copper sheets to form electrodes covering each of the inner end surfaces. The tank was filled with tap water which had enough impurities to form an electrolyte of a convenient resistance for the ranges of the bridge and the potentiometer.

Because of symmetry of the flow pattern through and around an imbedded transducer, a model was constructed to represent a quarter section of the transducer. It was attached to the wall of the tank midway between the two electrodes, with its sides parallel to the tank electrodes and its upper edge flush with the water surface. The dimensions of the model were 10 × 10 × 2.5 cm representing, therefore, a transducer with an L/W ratio of 0.125. Essentially, the model was a rectangular container to hold water of different resistivities. It was made of non-conducting materials; the edge material was $\frac{1}{8}$ inch thick and that of the two sides was $\frac{1}{16}$ inch thick. Each side was perforated with 225 holes in a rectangular grid. A brass machine screw was then turned part way into each hole and the protruding screw ends were sheared off. Consequently electricity could flow perpendicularly but not laterally through the model sides.

The model was filled first with a sample of the tank water and the area around the model was probed to evaluate distortion in the potential field caused by the walls of the model. It was found that the distortion could not be detected with the electrical system employed and it was assumed, consequently, that the effect of the model surfaces could be neglected.

Various concentrations of tap water, distilled water, and salt water were used in the model to obtain the desired conductivity ratios. In each case the potential drop across the sides of the model was determined by measuring the potential at 25 points on each side. Since the equipotential surfaces formed curves at their intersections with the model sides, the average potential of a side could not be determined directly. The potential values were plotted on graph paper, equipotential lines were drawn and the average for the area was graphically determined from the pattern formed.

Resistivities of the tank water and of the various model solutions were determined by placing samples in a non-conducting cylindrical test cell, 10 cm in length and 5 cm in diameter, the ends of which were closed by tightly fitting copper disks which served as electrodes. The resistance R of the cell was measured with the Wheatstone bridge and the resistivity r of each sample determined by

$$r = R(S/l) \quad \text{(ohm cm)} \qquad (11)$$

in which S is the cross sectional area of the cell and l its length.

The ratio of the current flow through the model to the current flow for an equal area in the undisturbed tank water was calculated with the relationship

$$I_m/I_t = (r_t/r_m)(E_m/E_t) \tag{12}$$

in which

I_m = current flow through model

I_t = current flow through an equal area in the tank

r_m = resistivity of model water

r_t = resistivity of tank water

E_m = potential drop across model

E_t = potential drop across distance in tank

Eq. (12) follows from Ohm's law after substitution with the relationship of (11) above. I_m/I_t is the analogue of X in (10) and r_t/r_m the analogue of k_t/k_s.

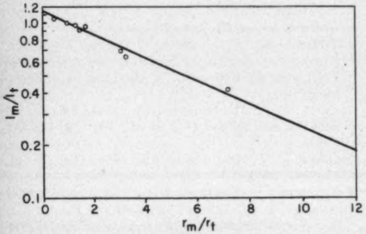

FIG. 3 – Relationship between current flow ratio and resistivity ratio (ordinate on logarithmic scale)

The following data were obtained:

r_t/r_m	I_m/I_t
0.14	0.417
0.30	0.640
0.325	0.689
0.60	0.954
0.67	0.910
0.73	0.970
1.00	1.000
2.23	1.060

Because an exponential relationship was predicted between X and k_s/k_t, their electrical analogues were plotted in semi-logarithmic co-ordinates as shown in Figure 3. It is seen that the experimental points approximate a straight line as expected. The line shown was placed by visual estimation with the requirement that it pass through the point 1.0, 1.0. Its equation is

$$\ln (I_m/I_t) = b(1 - r_m/r_t) \tag{13}$$

in which b is a constant found to be approximately 0.15. Eq. (13), rewritten as an exponential function, becomes

$$I_m/I_t = e^{b(1-r_m/r_t)} \tag{14}$$

which is the analogy of (10). Consequently, $b = a(L/W)$ and substituting $L/W = 0.125$ for the model used in the experiment, $b = 0.15$, and $a = 1.2$. Thus, (10) becomes

$$X = e^{1.2(L/W)(1-k_s/k_t)} \tag{15}$$

Figure 4 shows the curve of (15) for $L/W = 0.125$ and the experimental points obtained. This

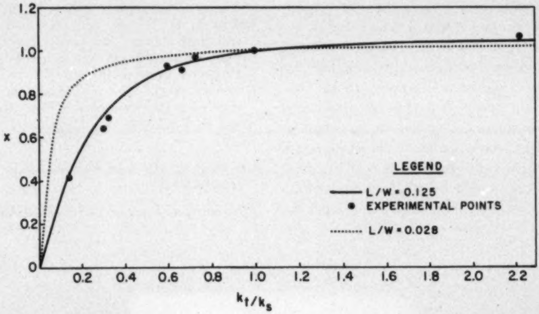

FIG. 4 – Relationship between heat flow ratio and conductivity ratio: $X = e^{a(L/W)[1-(k_s/k_t)]}$

is, of course, merely another representation of the information shown in Figure 3, but it shows also the curve in relationship to the limiting areas discussed earlier.

Application of results—Shown also in Figure 4 is the curve for an L/W ratio 0.028, an appropriate value for a heat-flow transducer used during the Great Plain Turbulence Field Program at O'Neill, Nebraska [*Portman*, 1957]. Since the transducer had steel cover plates approximately $\frac{1}{32}$ inch thick over the $\frac{3}{64}$ inch Bakelite element, the computed curve might not be valid for this case. Steel has a conductivity about 100 times that of the Bakelite, consequently the flow-pattern distortion caused by this transducer would be somewhat different from that of the simple model.

If an overall effective conductivity is used for the transducer, the curve might have meaning. An effective conductivity k_e was computed using the following equation

$$k_e = \frac{L_1 + L_2}{L_1/k_1 + L_2/k_2} \approx 0.0016 \text{ cgs units}$$

in which the subscripts 1 and 2 refer to Bakelite and steel respectively. *Buettner* and others [1957] measured the soil thermal conductivity at the O'Neill test site and have reported that the values at 2.5 cm depth ranged from 0.8×10^{-3} to 1.3×10^{-3} for the observation days for which transducer data are given by *Portman* [1957]. The corresponding k_t/k_e ratios are approximately 2 and 1.2. If the curve is correct for this transducer and if the empirical constant $a = 1.2$ is applicable for an L/W ratio of 0.028, Figure 4 shows that the O'Neill data should have less than +2 per cent error due to flow pattern distortion.

Conclusions—Figure 4 reveals that for conductivity ratios between 0.8 and 2.0 an error of less than five per cent would be involved when a transducer having a thickness-width ratio of 0.125 is used. If the transducer thickness is $\frac{3}{64}$ inch, the standard thickness of a type of transducer commercially available, it could be as small as $\frac{3}{8}$ inch square and have distortion errors no larger than those indicated by the solid line in Figure 4. Such a transducer would be much more satisfactory for use in wet soil than would the larger devices currently being used, because of the moisture barrier problem previously discussed. Several could be used at one depth to obtain more representative measurements and they could, presumably, be connected in series in order to increase the electrical output if necessary.

The analysis shows, further, that if a transducer with an L/W ratio on the order of 0.1 is to be used in soil whose thermal conductivity is likely to change with time it is best to have the transducer conductivity somewhat larger than that of the soil since the error is small and only slowly changing between conductivity ratios of 1 and 2.

Acknowledgments—This contribution is based on a chapter of a dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy at Johns Hopkins University. The author is indebted to George S. Benton for many suggestions and for helpful criticism in the analysis of the problem.

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Interception Losses in Grassy Vegetation

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Abstract—Studies of the interception process in grassy species are reported for a series of laboratory tests. Procedures, equipment, and techniques were developed to determine the magnitudes of rainfall interception on grasses and to measure the resultant losses. It was found in vigorously growing grass plots that the evaporation of a given amount of intercepted moisture was accompanied by a like reduction in the amount of evapotranspiration from the plants. Total moisture use was approximately the same in plots with wet and dry leaf surfaces. The interception storage component and precipitation passing through the vegetative canopy as combined stemflow, throughfall and drip (STD) were measured to determine the relationships and magnitudes. Storage capacities were observed to agree essentially with those reported by other investigators although some variations can occur with different storm types and intensities. Values of STD were found to be quite significant even at the beginning of small storms.

INTRODUCTION

Savings of water by replacing indigenous brushlands with grass on large acreages in the West are predicated on several basic hydrological relationships. Small watersheds so converted have yielded significant increases in total runoff [*Burgy*, 1958]. This greater water yield may have two explanations: (1) grasses intercept less water than brushy types, and (2) grasses use less water than brush.

Long recognized as important in precipitation disposal is the interception of precipitation by the aerial portion of vegetation, with succeeding disposal into the atmosphere or to the ground. Research in the United States on the interception process in tree-type cover has been considerable, beginning with the classic contributions of *Horton* [1919] and continuing up to the present. Somewhat more limited, yet quite intensive, is work on interception in brush and shrubby vegetation. Still more limited is our knowledge of the interception process in grasses and other low-growing plants.

Precipitation gages of various kinds can be installed in tree types and certain brushy types of vegetation, under the vegetative canopy and adjacent to it, to determine differences in 'ground rainfall.' In low-growing, relatively more dense vegetative types, however, this straightforward method presents obvious mechanical and spatial difficulties.

Clark [1940], in experiments in Nebraska, placed catch pans on the ground beneath grass plants in the field. Low-growing, mat-forming grasses were cut off at the surface and moved to the laboratory, where they were replaced in natural position on screens and then sprinkled. In the field trials, interception was determined by the percentage of rainfall that did not reach the pans. In the laboratory, interception was determined by the portion of water applied that was not recovered beneath the screen. The interception values of Big Bluestem grass varied from 84 pct, with 0.125 inch of rainfall in 30 min, to 47 pct, with 1.0 inch of rainfall in one hour. The low-growing, mat-forming grasses had much lower interception capacities.

In tree or brush types, or in fact any large plant, the flow of water down the stems can be measured by stem collars connected to measuring devices. *Haynes* [1940], working with various crop covers, measured stemflow in that way and also used wax-floored catchment basins to determine stemflow under oats, timothy and blue grass, with erratic results and did not report stemflow.

The inherent difficulty in making measurements for low-growing crops probably accounts for the relative scarcity of information in this field. The obvious need for additional basic data on the interception process in grassland types has led to the present study.

PROCEDURES

It was felt that full evaluation of the interception process in grasses requires a system involving the complete plant-soil-water complex. Equipment and techniques were developed to permit studies of evapotranspirational use by growing plots of grasses subjected to artificial rainfall.

In large tanks of nutrient solution, grasses were planted and grown on test plots constructed of square aluminum frames: a bottom of hardware cloth was attached; excelsior was packed inside the tray and covered with a layer of cheesecloth; and a layer of hardware cloth was attached to the top, forming a sandwich arrangement on which to grow the crop. The individual baskets or plots could be moved to individual weighing pans of nutrient solution resting on scales.

The original weighing mechanism was the scales from a Bendix-Friez weighing-recording rain gage. The pan areas were made ten times as large as the eight-inch rain gage area, expanding the gage scale by ten. But the system did not prove to be accurate enough for the demands of the experiment. Four grocery checkout scales proved more accurate and reliable, although non-recording.

The water-culture technique eliminated the complication of measuring soil-moisture values. The studies were divided into two parts: a series of tests with plots alternately wetted and allowed to dry to determine the total evaporational use (see Section I); and an evaluation of interception storage as distinguished from stemflow, throughfall, and drip (see Section II).

SECTION I

Three different cover types were studied, (1) sunflower plants (used in the initial tests to study methods and techniques), (2) a pure stand of soft chess, and (3) a mixed stand called range mix, consisting of Hardinggrass, alfalfa, narrow leaf trefoil, rose clover, crimson clover, subclover, soft chess, orchard grass, smilo, and tall fescue.

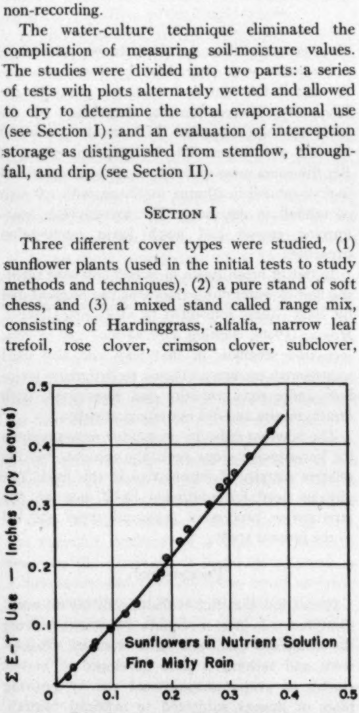

FIG. 1 – Accumulated evapotranspirational use, relationship of wet-leaf system to dry-leaf system, sunflower plants

FIG. 2 – View of grass plots on scales

Sunflower tests—Sunflower plants grown in nutrient solution, available from another experiment, were moved into pans and supported upright by submerged frogs. Plants in Pan A were wetted to drip point by a fine water spray. The water spread out over the surfaces with no tendency to form droplets. When the plants in Pan A were dry, the process was applied to the plant leaves in Pan B. The cycle could be repeated several times in one day, with automatic recording of the amount of water added and total amount of water used. Figure 1 shows the relationship of accumulated evapotranspirational use of wet-leaf systems to dry-leaf systems for 18 successive rainfall applications. These results are included here since they showed similar responses to the grass tests which followed.

Observe that, although moisture was retained by leaves and did evaporate, wetted leaves caused no excess water loss to the full system. In fact, the opposite is indicated: total usage was less for wetted plants.

Adding or subtracting small aliquots of water to or from the weighing pans indicated that much greater accuracy and reliability could be obtained with springless scales than from the spring-type rain-gage scales. Therefore, these scales were used for the remainder of the experiments (Fig. 2).

Hamilton and *Rowe* [1949] defined interception as "the process in which rainfall is caught by the vegetative canopy and redistributed as throughfall, stemflow and evaporation from the vegetation." This is a completely satisfactory definition. Interception storage can be defined as a depth of moisture that is retained on a given surface area. Interception storage accumulates, up to essentially a constant depth, as the rain continues, though it can be modified somewhat by winds and type of storm. This depth can then be termed 'interception storage capacity,' essentially the same value

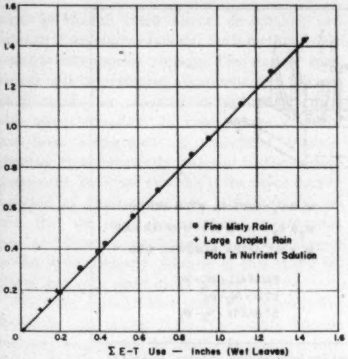

FIG. 3 – Accumulated evapotranspirational use, relationship of wet-leaf system to dry-leaf system, range-mix plots

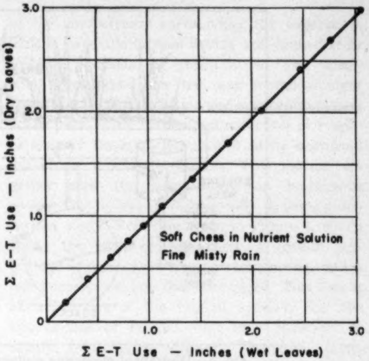

FIG. 4 – Accumulated evapotranspirational use, relationship of wet-leaf system to dry-leaf system, soft chess plots

as later will be termed 'gross interception loss.' From the results with sunflowers, 'interception loss' appeared to require re-defining into two terms: 'gross interception loss' and 'net interception loss.' Gross interception loss is "that portion of the rainfall that is retained on the aerial portion of the vegetation," which is part of the definition of interception loss as provided by Hamilton and Rowe. Net interception loss should be defined as that portion of the rainfall retained on the aerial portion of the vegetation that has no net effect on the soil water consumption of the plant. Net interception loss is the only truly lost moisture insofar as growing plants are concerned. In the trials where only growing and transpiring plants were used, net interception losses must be distinguished from interception storage. The following studies showed that no net interception loss occurred with grasses that were actively transpiring.

Range mix—The seed planted for the range mix trials produced a grass stand consisting principally of tall fescue and soft chess. For the data shown in Figure 3, cover density was nearly 100 pct, height of leaves ranged from about eight inches at the beginning of the trials, to about 16 inches at the end, three weeks later. Mowing the plots yielded an air-dry harvest of about 1500 lb/ac. All plants were apparently growing vigorously, and essentially similar in all four replicates. The systems were maintained in environments that were identical in wind movement, insolation, relative humidity, and temperature. The dense growth prevented rapid drying below the exposed, upper levels. Therefore, at least a full day was required for each trial. Whereas the sunflower leaves had wetted evenly, rainwater on the grasses collected as droplets. Figure 3 shows total water use as determined by the weight differentials of paired plots. Accumulated evapotranspirational use involved both misty rains and large-droplet rains, denoted by circles and crosses on the graphs. Here again note that no true loss of moisture occurred when the complete system is considered.

Soft chess—Figure 4 shows the results of trials of misty rain on a pure stand of soft chess. This grass stand was mature and extremely dense. Harvesting at the completion of the trials gave an air-dry yield of 4500 lb/ac. Lodging had choked and killed most of the center areas of each plot. Therefore, about ¼ to ⅓ of the canopy was not a transpiring cover.

SECTION II

Interception storage, stemflow, throughfall, and drip—*Horton* [1919] calculated the interception storage capacity of rye as 0.047 inch. *Musgrave* and *Norton* [1937] experimentally determined other interception values: corn, 0.145 inch; alfalfa, 0.140 inch; clover, 0.123 inch. These values gave no consideration to moisture flowing down the stems of the plants. *Grah* and *Wilson* [1944] determined an interception storage capacity of

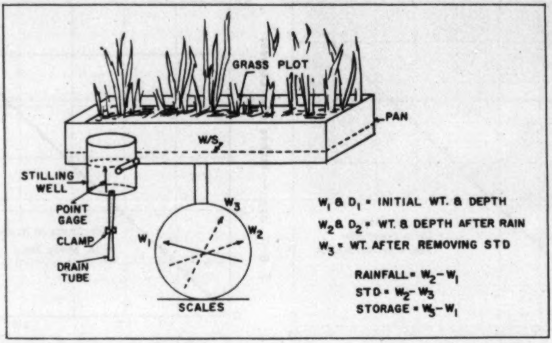

FIG. 5 – Diagram of measuring equipment for interception, storage, and STD

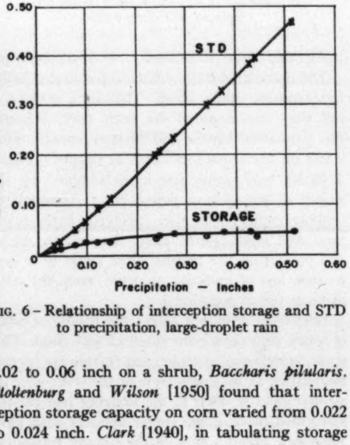

FIG. 6 – Relationship of interception storage and STD to precipitation, large-droplet rain

0.02 to 0.06 inch on a shrub, *Baccharis pilularis*. *Stoltenburg* and *Wilson* [1950] found that interception storage capacity on corn varied from 0.022 to 0.024 inch. *Clark* [1940], in tabulating storage capacities, reported interceptions varying from 1.21 inches on Big Bluestem (68 pct of 1.78 inches of rainfall), to 0.33 inch on slough grass (73 pct of 0.45 inch rainfall). His values seem exceptionally high. Clark stated that stemflow amounts were small, but it may be asked whether his method accurately assessed them on grasses.

In the present study no attempt was made to separate stemflow, throughfall, and drip (abbreviated STD herein) into components; they were assessed as a whole. The trials reported are for the range mix stands. The plots were representative of natural northern California rangeland cover insofar as the canopy was concerned. The grass was about ten inches high (therefore presenting less storage surface than may have been the case in previous investigations).

Method—Quantitative measurements of storage and STD were made by a slight modification of equipment and use of the same plant plots used in Section I. A stilling well with a submerged point gage was connected to one of the weighing pans. An initial depth of solution, at the crown of the plants, was established on the point gage. Rainfall was then applied to the system, after which the SDT water was removed to the original depth by extracting it through a hole in the bottom of the stilling well. This permitted both weight and volume determinations of the amount of water passing through the canopy as STD. The difference between final weight (after extraction of STD) and the original weight was the amount of storage on the leaves, expressed in inches over the area. Figure 5 diagrams this equipment. A check plot, on adjacent scales, provided values for consumptive use during the period.

Figure 6 shows the results of several STD and storage determinations. Transpirational uses were very low in most cases. It will be observed that storage accumulated up to values of 0.041 to 0.048 inch. It was possible to create an additional increment of storage, slightly over 0.01 inch, by applying more rainfall in a fine mist. This is not included in Figure 6.

DISCUSSION

Previous investigations of interception loss in the literature dealt almost entirely with differences in rainfall catch above, or outside, and beneath a vegetative canopy. Such methods only evaluate interception storage. The storage component will be evaluated accurately only in cases where means are provided to capture or otherwise assess stemflow. In cases where stemflow has been disregarded or considered inconsequential, it is incorrectly included in the storage component. In either case this is the value usually reported as interception loss. It appears, therefore, that the terms 'interception,' 'interception loss,' and 'interception storage' are often used more or less synonymously. Results of this study indicate that such usage is not proper.

The trials reported here show that interception obviously was taking place (the plants became wet) and evaporation followed (the plants dried). This could not be termed true interception loss, however, for when one considers total moisture use from the complete plant-soil-water complex, the use is effectively the same in both wetted and non-wetted systems.

Moisture could be lost in these trials by transpiration, evaporation from the nutrient solution, and evaporation of the intercepted 'rainfall.' Evaporation from the nutrient solution was very low, because of its shaded and protected location, and was essentially the same in all plots during any run. The distinguishing factor then becomes the moisture on the leaf surfaces. Although such moisture was evaporating from the leaves, a like reduction of transpiration was effected, as indicated by these results.

Several past workers, *Christiansen* [1942] and others, reporting on sprinkler investigations have recognized this and have supposed a reduction of transpiration when leaf surfaces were wetted. *Harrold* and *Dreibelbis* [1951] approached this same conclusion when they reported that dewfall or rain in the night conserved soil moisture the following day. The plants in the lysimeters were wet at the beginning of the day.

Under any evaporative conditions, wet leaves transpire less water than do dry leaves. Since grass leaves do not actually wet, but merely retain water droplets, the coverage is not uniform. Therefore, the energy available for evapotranspiration on wet leaf areas is used to vaporize free water from the droplets, in contrast with a continuing normal (or nearly normal) transpiration rate from the dry areas of the leaves. The reduction of transpiration is related to the decrease in vapor-pressure gradient from leaf stomata to atmosphere that is occasioned by the increased vapor content of the microclimate surrounding the vegetation. This is particularly true during and immediately following periods of precipitation. The somewhat special condition that may prevail at night with regard to transpiration and interception losses is complicated by an unequal reduction of evaporation and transpiration as well as by nocturnal variations in climatic factors. This matter, together with the relationships on herbaceous species that do wet more uniformly, is being given further study. Referring again to Figure 4, which shows the trials on soft chess, a certain percentage of this cover was non-transpiring, and a net interception loss did take place. This loss is about 15 pct of the rainfall applied. But the applications of rainfall were only sufficient to satisfy interception storage. Therefore, interception loss was 15 pct of the interception storage capacity, or about 0.0075 inch in the period. As has been noted previously, these plots contained a considerable percentage of dead grass. Intercepted moisture on such dead surfaces evaporated, whereas transpirational losses from such dead surfaces did not occur. Therefore a net interception loss to the system took place. This leads to the conclusion that the whole complex of surfaces, living and dead, transpiring and non-transpiring, maximum transpirational use and less than maximum transpirational use, must be considered in discussing interception losses for grasses or in fact any plant cover. This complex could be affected by season of the year, type and condition of plants, management of cover, and even the time of day. Further work is planned to investigate these factors.

SUMMARY AND CONCLUSIONS

Methods and equipment were devised to study the interception process in grasses. Tests on small, growing grass plots showed that the entire plant-soil-water-rainfall complex must be considered in evaluating the net effect of this intercepting canopy on precipitation disposal.

On transpiring grasses under rainfall such losses as may occur from the aerial part of the plant are accompanied by an equal reduction of moisture use from the 'soil.' When a portion of the grassy vegetation is dead, a net interception loss is observed. This loss amounts to some percentage of the storage capacity of the vegetation. The magnitude of the net loss seems to be related to the ratio of non-transpiring to transpiring surfaces.

Increases of water yield following conversion from brush to grass, mentioned earlier, are supported by the results of this study. Part of this increase is due directly to lower net interception loss from grasses. The influences of grass cover on soil condition, infiltration and hydraulics of overland flow are also important considerations.

Results show that the interception storage capacity of a grassy canopy is not satisfied by a rainfall equal to this storage capacity. Rather, storage is satisfied in increments as the rainfall progresses, so that a large portion of the rain reaches the ground even at the beginning of small storms.

It seems desirable to re-examine the terminology heretofore used in interception studies, bearing in mind the necessity for considering the complete system. The storage capacity of the plant does not necessarily represent the magnitude of net interception loss.

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Shallow Ground Water and Tile Drainage in the Oxnard Plain

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Abstract—A study of the hydrology of the shallow ground waters of the Oxnard Plain, Ventura County, California, was made using a network of piezometers at 10 and 20 ft below the surface. Mean depth to water is 6.8 ft and shows little difference between January and June readings during the years 1953–1956. The perched water table slopes to the south and southwest. It is only slightly above sea level near the coast. Piezometric head differences established the presence of a downward gradient over most of the area. The shape and rate of recession of the water table in tile-drained land and tile effluent rate were measured at various sites. Twenty-two per cent of water applied is discharged from tile lines as waste. Equipment and technique for hydraulic conductivity measurement in unstable soils is described.

Introduction—Field investigations were carried out on the Oxnard Plain, in the southwest portion of Ventura County, California. This is a rather low-lying area adjacent to the coast, originally saline, reclaimed by drainage with subsequent leaching. (It is understood that a large measure of the success of drainage in this area belongs to Walter W. Weir, Drainage Engineer, Emeritus, of the University of California, who gave considerable expert advice to local people planning the works.) It now supports a highly productive agriculture, notable products being lemons, lima beans, and off-season vegetables. Studies were confined to the area south of the Santa Clara River and west of Calleguas Creek. These are the two main drainage channels of the plain, and run approximately west and south respectively. They discharge into the Pacific Ocean which forms the western boundary.

Annual rainfall averages about 14 inches but was below normal during two years of this investigation. Drainage from the area is accomplished by means of an extensive system of tile drains and a relatively small number of open ditches (Fig. 1). Farm ditches are being replaced gradually by collector lines. Ditch maintenance, weed control, and the loss of valuable land are thus eliminated. The lateral tile lines usually discharge into collection lines from which the water flows to the district ditch system, thence to the ocean via one of the main drainage channels. Very few individual laterals suitable for effluent measurement were found discharging directly into ditches.

Objectives of the investigation were (a) to make a general survey of the area to determine the facilities that had been required to create a highly productive agriculture on land previously almost worthless; (b) to evaluate the shallow semi-perched ground-water levels resulting from the drainage measures utilized; and (c) to study the mechanics of the movement of ground water to the tile drains to provide more rational design criteria.

Soils and stratigraphy—Soils in the Oxnard area are recent alluvium from sedimentary rocks and old valley fill material which have been transported and deposited by the Santa Clara River. The majority are classified as Yolo with a few areas in the Dublin series. The surface soils are generally fairly homogeneous to a depth of six to eight feet and generally overlie much less permeable silts and clays. This subsoil material was laid down on the flood plain by the Santa Clara River and there is little continuity to the strata. Deposits typical of flood plain deposition are found ranging from fine gravel through sands, silts, and clays, at depths between 10 and 20 ft below the surface. Auger-hole samples were taken down to 16 ft at the three major tile-line investigation sites, but mechanical analyses did not indicate the presence of a true clay. From information gathered from local farmers, it appears that an impermeable barrier does underlie parts of the plain. The shallowest depth reported was 14 ft below the surface. Stratigraphic information obtained while jetting in piezometers to 20 ft below the ground surface indicated no continuous clay layer, but rather a series of clay and silt lenses of low permeability which were interspersed with lenticular deposits of fine sand, coarse sand, and fine gravel of high permeability. South of Highway 101 between Rice and Las Posas Roads, a series of piezometers jetted to 30 ft indicated that similar conditions prevailed between 20 and 30 ft with sand layers constituting in some cases more than half of that 10-ft interval. No thick clay layers were present down to 60 ft at field Site 3.

The lenticular silts and clays provide an ef-

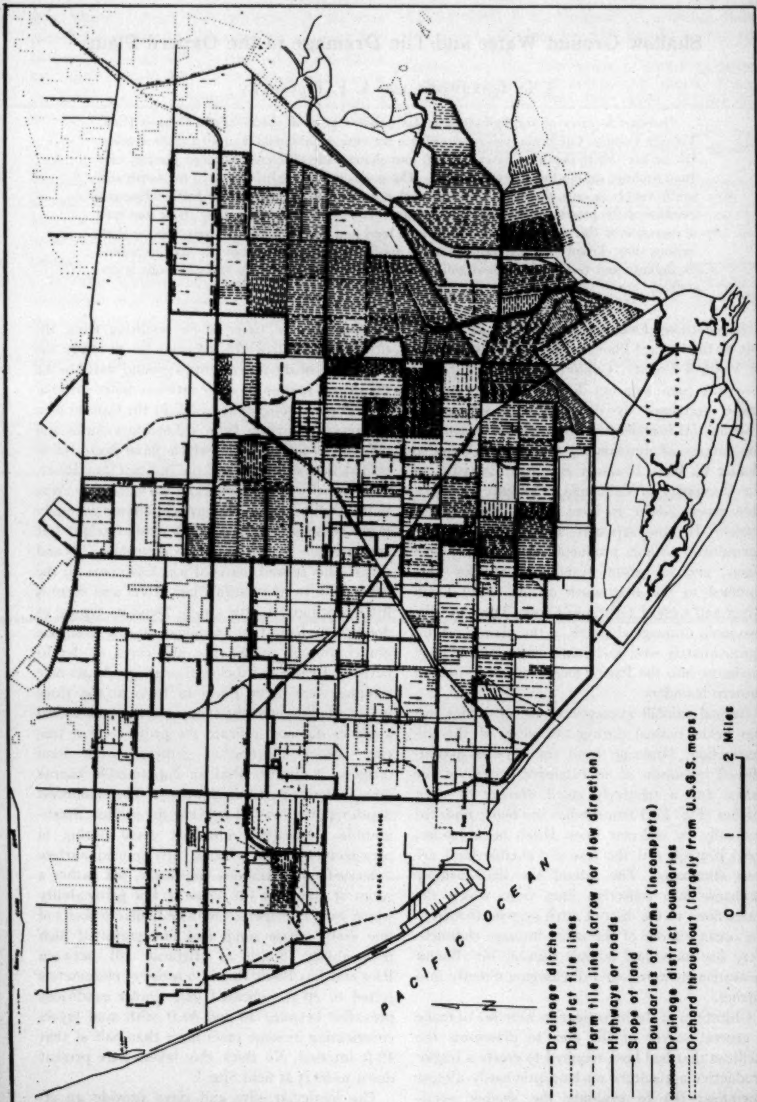

PACIFIC OCEAN
N
Drainage ditches
District tile lines
Farm tile lines (arrow for flow direction)
Highways or roads
Slope of land
Boundaries of farms (incomplete)
Drainage district boundaries
Orchard throughout (largely from U.S.G.S. maps)
0
1
2 Miles

FIG. 1 – The drainage facilities of the Oxnard Plain, Ventura Co., California, 1952

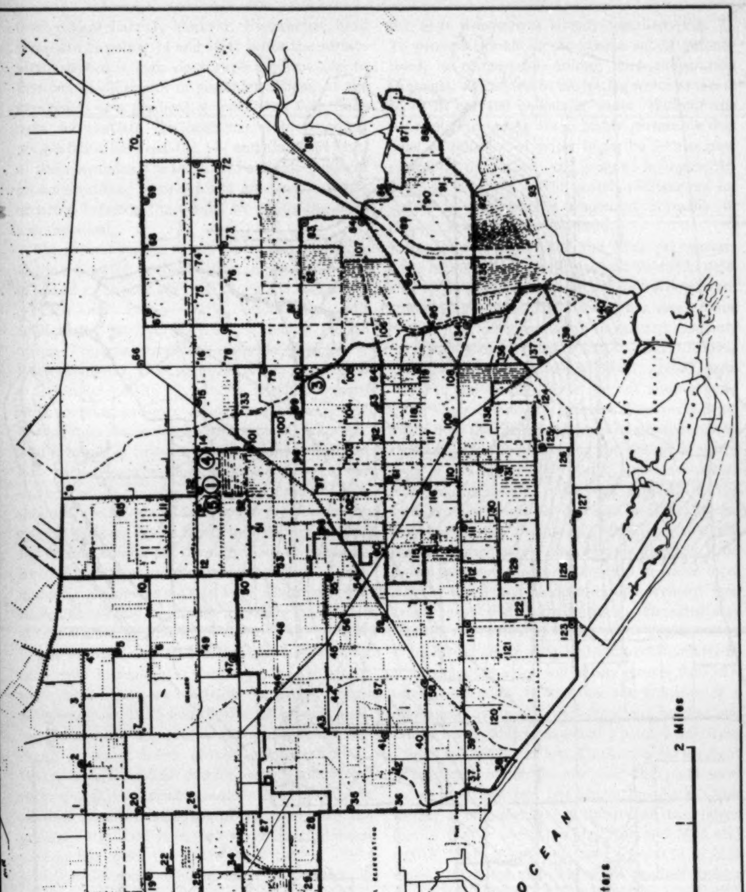
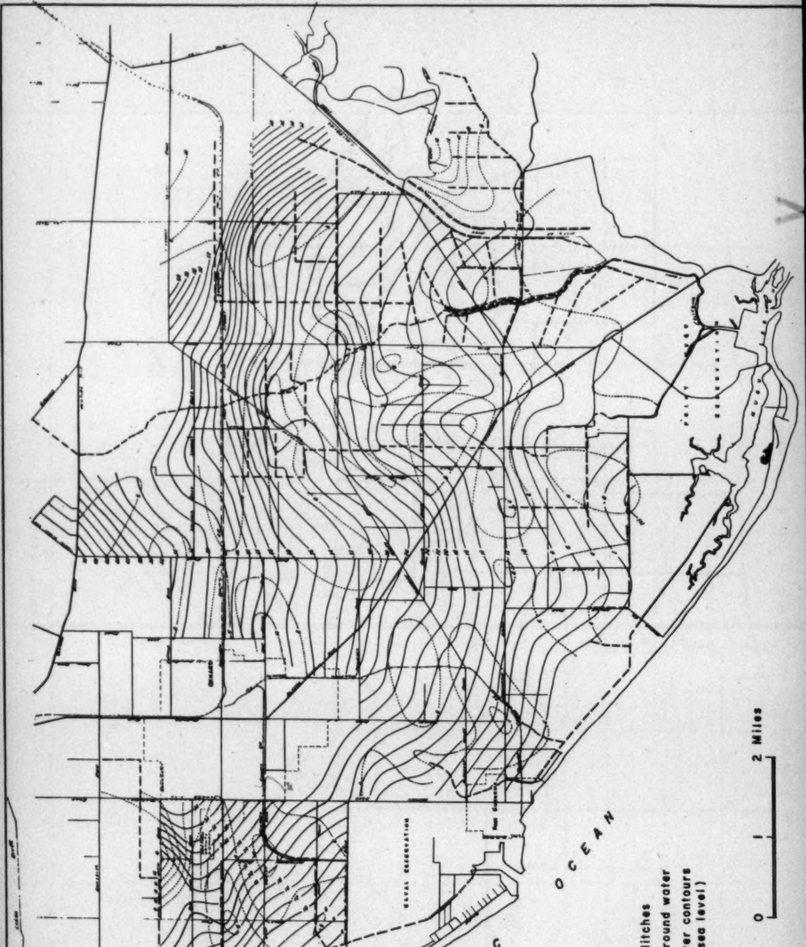

PACIFIC OCEAN
N
• 11-ft Piezometers
⊙ 11- and 21-ft Piezometers
○ Field sites
0
1
2 Miles

FIG. 2 – Piezometer locations and field sites


PACIFIC OCEAN
Naval Reservation
Port Hueneme
Oxnard
N
0
1
2 Miles
Drainage ditches
Depth to ground water
Ground water contours (ft above sea level)

fective local barrier, however. Piezometric head measured at points 14 and 20 ft below the surface often showed a high downward gradient (up to five feet of difference in piezometric head at the two points or a gradient of more than 0.8). Such data substantiate the existence of low vertical permeability between the 14- and the 20-ft level at those locations. On the other hand differences of piezometric head were small in areas where sands occurred between the depths at which the head was measured.

The ground surface slopes gently and uniformly to the southwest, with elevations ranging from 100 ft inland to almost sea level along the coast.

Water-table survey—Little information was available on the hydrology of the shallow ground water. Previous surveys [*California Division of Water Resources*, 1933, and 1953; *U. S. Department of Agriculture*, 1920] have shown that the Oxnard Plain overlies pressure aquifers which were still flowing from water-supply wells some 20 years ago. The presence of artesian water clearly indicates a flow barrier between the deeper aquifer and the surface, which is borne out by the existence of a shallow perched water table a few feet below the ground surface. Water levels in wells penetrating the Oxnard aquifer have now dropped to below sea level. Figure 2 shows the locations of 140 ⅜-inch diameter piezometers 11 ft long which were installed on roughly a half-mile grid over the area, to obtain shallow ground-water elevations.

The network was read in January and June of each year beginning in January 1953. Readings were taken using an electrical sounder [*Donnan* and *Bradshaw*, 1952] and plotted on a map showing water-table elevations above sea level and depth to water below ground surface (Fig. 3). Water-table elevations determined in this manner show a positive seaward gradient at all points. At no time since the beginning of the survey has the ground-water level fallen below sea level although piezometers near the coast show only a slight positive elevation. Ground-water movement, in general, follows the main surface drains, Revlon Slough and Calleguas Creek, and flows in a southerly direction to the coast.

Deep percolation—The usefulness of piezometers to different lengths at the same location to determine vertical gradients has been firmly established in other areas [*Reger* and others, 1950]. A network of 21-ft piezometers on approximately a one-mile grid was installed by jetting as described by *Pillsbury* and *Christiansen* [1947]. These piezometers were located within a foot or two of the 11-ft piezometers already installed (Fig. 2). To penetrate some of the coarse sands encountered, a commercial drilling mud preparation (Aquagel) was added to the jetting water at a rate of 10 lb per 100 gallons of water. Without the Aquagel these sands are so highly permeable that none of the flow of water from the jetting pipe returns to the surface, and progress is impossible. After flushing with clean water, piezometers installed in this manner responded normally to changes in the piezometric head.

Readings of both 21-ft and 11-ft piezometers were taken at six-month intervals in 1953, 1954, and 1955. These data show a definite downward gradient over the entire plain with a mean value of 0.05. Site 3 showed mean downward gradients during 1954 of 0.11, 0.1, 0.1, 0.14, and 0.18 over the intervals 7–12, 12–15, 15–21, 21–27, and 27–63 ft respectively. Time did not allow a complete water balance to estimate deep percolation losses over the plain but a very rough approximation was made by measuring the change in water level in two piezometers during a summer period when no irrigation water was applied in the vicinity. The water levels were well below the neighboring tile drains and slightly above the bottom of the nearest ditch (¼ mile distant). If no lateral movement occurs, the drop in water level may be attributed to downward movement into deeper zones. Below the fairly non-stratified surface soil the particular nature of the profile makes it unlikely that the mean hydraulic conductivity in a horizontal direction will be any greater than in a vertical direction. In any case the influence of a drainage ditch is somewhat localized, so that the rate of water-table recession at a point ¼ mile from a ditch is likely to be low. The horizontal gradient is extremely small. In one case the piezometer water level was two feet above the ditch water surface ¼ mile distant; in the second case seven feet in ¾ mile which are gradients of 0.0015 and 0.0018. Vertical gradients vary from 0.15 to 0.30 depending on the elevation of the perched surface (assuming the mean depth of the Oxnard aquifer to be 200 ft.).

The assumption made above regarding the likely equality of horizontal and vertical hydraulic conductivity may be incorrect; but even if the horizontal conductivity exceeds the vertical by 100:1, the horizontal gradient would still hardly exceed the vertical gradient.

To interpret the change in water level in the soil in terms of true water quantity the specific yield was determined from 36 core samples taken from a depth of five feet. Moisture content at ⅓ atmosphere (assumed equivalent to field capacity) and bulk density were determined. The mean specific yield of 16.1 pct shows remarkable agreement with the 16 pct found by the State Division of Water Resources for the deeper aquifer.

The two piezometers observed both gave, perhaps fortuitously, a change in level equivalent to 0.9 ft of water per year. At the very least one-half of this or 0.45 ft/yr may be attributed to deep percolation and it is possible that all 0.9 ft percolates through to the deeper zones. The total extent of the area covered by this study is around 32,000 ac, which means an annual recharge to the deeper zones of 14,000 ac ft of water (using the conservative figure of 0.45 ft). This is a significant amount when the annual pumping draft is considered to average 1½ to 2 ft, or at maximum 64,000 ac ft per annum. Almost one-quarter of the annual draft may actually be replenished by deep percolation. The quality of the shallow water is poor. Mean electrical conductivity (EC) from 20 samples was six millimhos/cm. To give some idea of the original salinity status of this area note that on land that was tiled during the course of the investigation, the EC of the tile effluent was 46 millimhos/cm after the third leaching.

Tile-drain performance—Three locations were chosen for tile-drain investigation (Sites 1, 2, and 3, Fig. 2) and measurements of effluent rate, cumulative discharge, hydraulic conductivity, and water-table recession following irrigation were made at each site. Originally measurements following rainfall were expected to provide some reliable information. Natural precipitation tends to be more uniform than irrigation, and the quantity of water applied is easily calculable from rain gage figures. Unfortunately, the only rainfall of sufficient intensity or duration to raise the water table appreciably also raised the drainage ditch level above the lower end of the tile drain. Investigation of drainage characteristics of tile lines were therefore confined to the summer irrigation season. Three tile lines were selected and the outlets equipped with tipping buckets. Plots of the effluent rate versus time are shown in Figure 4 for Sites 1 and 3. The initial rates are not maximum for these tile systems since effluent data with the soil saturated to the surface were impossible to obtain.

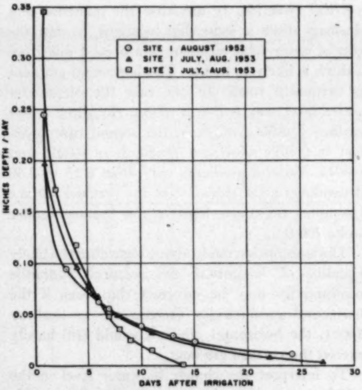


FIG. 4 – Tile discharge rates

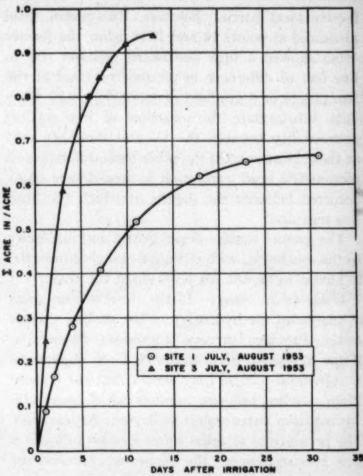


FIG. 5 – Cumulative tile discharge

Cumulative discharge—Figure 5 shows the cumulative discharge at Site 1 and Site 3 in 1953. The 1952 records of Site 3 are meaningless because the title line was found to be partially plugged with eucalyptus roots. On the other hand, in 1953 with a normal irrigation cycle, there was no flow before irrigation and measurements were made until flow again ceased. The irrigation was light, the water table rose to a maximum of 0.15 ft above the top of the tile and yet 27 pct of the water applied

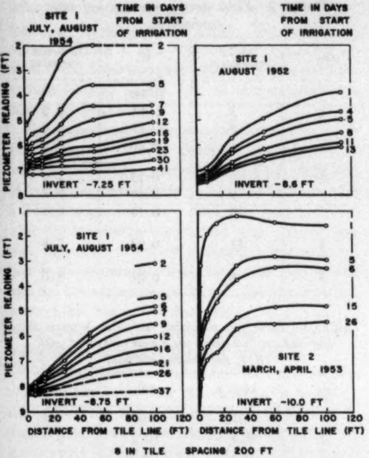


FIG. 6 – Water-table recession

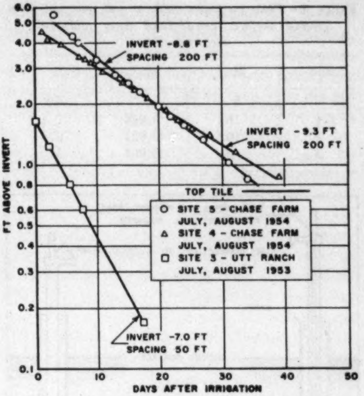


FIG. 7 – Midpoint recession, Sites 3, 4, and 5

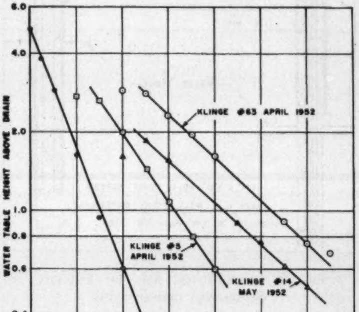


FIG. 8 – Midpoint recession, data from *Childs* [1947] and *Klinge* [1955]

was ultimately discharged to the ditch as waste.

Total cumulative discharge figures for three irrigations were 0.66, 0.94, and 0.96 acre inch per acre. Including drainage directly into ditches 1.0 acre inch per acre would appear to be a representative figure for the quantity of excess leaching water applied per irrigation. The annual pumping draft is 18 inches which means that, assuming four irrigations per year, $\frac{4}{18}$ or 22 pct of applied water is ultimately discharged as waste. The U. S. Salinity Laboratory method of computing leaching requirement, using the ratio of the EC of water applied to that of the drain effluent, yields 1.4/6.0 or 23 pct. It appears that on the basis of the above calculation the amount of leaching water used is not excessive. Approximately half of the total effluent is discharged in the first $\frac{1}{8}$ of the flow period. However, a detailed study of salt balance in this area might lead to a reduction in the presently excessive pumping draft on the deeper artesian aquifers.

Water-table recession—Piezometer readings on the recession of the water table following irrigation were made at all locations. Piezometers of three different lengths were originally installed at each point but gave identical readings in the shallow zone down to the tile line. Thereafter a row of single piezometers on one side of the tile was used with an electrical sounder to establish water levels. Figure 6 shows examples of the type of recession curves obtained. One feature which attracts immediate attention is the very rapid drawdown over the tile line. In one set of readings indeed the water table at the midpoint stood almost eight feet above the top of the tile line, while the piezometer inserted at the tile line indicated no water above the tile at this point. A disturbance of the

TABLE 1 – *Time for water table to fall one foot from ground surface, extrapolated from midpoint recession curves*

Site	H	c	
	ft		day
1	8	0.028	2.1
2	10	0.021	2.2
3	6	0.061	1.3

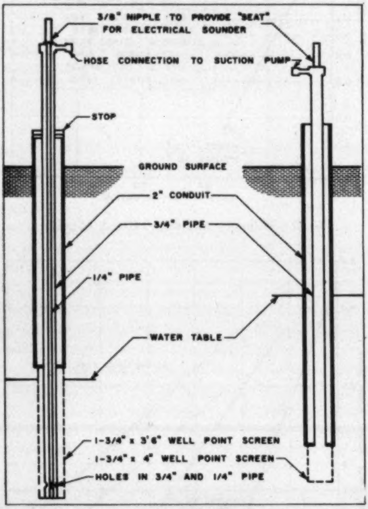

3/8" NIPPLE TO PROVIDE "SEAT" FOR ELECTRICAL SOUNDER
HOSE CONNECTION TO SUCTION PUMP
STOP
GROUND SURFACE
2" CONDUIT
3/4" PIPE
1/4" PIPE
WATER TABLE
1-3/4" x 3'6" WELL POINT SCREEN
1-3/4" x 4" WELL POINT SCREEN
HOLES IN 3/4" AND 1/4" PIPE

FIG. 9 – Screened test hole for hydraulic conductivity measurements

original stratification in the trench dug to lay the tile line can lead to this type of recession curve. In this particular case it was difficult to confirm this by soil samples although a clay layer at a depth of five to seven feet close to the tile line was not present above the line. However, the same layer did not occur at the midpoint between lines either. It would appear that anisotropy or stratification, although not continuous, is sufficiently pronounced in this locality to make the trench effect quite apparent.

TABLE 2 – *Field measurements of hydraulic conductivity*

Site	No. of Measuments	*K*	Coefficient of variation
		ft/day	
1	3	2.01	0.2
	4	2.17	8.2
	3	3.26	3.7
2	8	0.13	1.9
	9	0.19	0.3
	10	0.14	0.2
4	11	0.93	7.8
5	8	0.61	8.0

TABLE 3 – *Time for midpoint recession between three feet and two feet above tile invert compared with K/f; tile spacing constant*

Site	Mean K	K/f	Time
	ft/day	ft/day	day
1	2.5	10.2	6
2	0.15	0.94	7
4	0.93	3.8	5.8
5	0.61	2.5	7

In all four recession rate plots the various stages in the recession of the water table are far from being parallel. The fall at midpoint is in all cases considerably greater than the fall near the tile itself. Clearly the succession of nearly parallel water surfaces as found by *Childs* [1947] is missing and will in practice never be present with drain spacings of this order (200 ft). For a 200-ft spacing the stages would no longer be parallel when the water-table height at the midpoint is less than about 25 ft above a drain [*Childs*, 1947, Fig. 3]. Drains are not laid at such depths and consequently the parallel surface stage is absent. The relationships between the surfaces in this nonparallel region are consequently the ones of major practical interest, and more particularly at the midpoint between drains where the water table will be highest.

Plots of midpoint height of water table above drain tile invert yielded a simple exponential function which was further confirmed by subsequent midpoint water-level readings in various locations as shown in Figure 7. The electric analogue results obtained by *Childs* [1947] and some unpublished data by *Klinge* [1955] are plotted in Figure 8.

If this exponential relation between water-table height and time is extrapolated, the time for the water table to fall one foot from the surface may be computed from

$$\log H - \log (H - 1) = cT \qquad (1)$$

where H is the depth in feet of the tile invert below the ground surface, T is the time in days, and c is the slope of the curve. The results are shown in Table 1. It is interesting to note that for Sites 1 and 2 the computed recession rate from the surface is close to one foot in two days as suggested by *Neal* [1934].

Hydraulic-conductivity measurements—Preference was given to *in-situ* methods (the auger-hole and the piezometer methods) for the determination of hydraulic conductivity. A few trial borings with a 2-inch auger indicated that open-hole methods were not feasible in the Oxnard area. A technique was, therefore, necessary to install a screened test hole in these unstable soils. Moreover the method had to be adaptable to measurements with the water table below five feet. The ground water is rarely closer to the surface except immediately following an irrigation or heavy rainfall.

The test borings indicated that continuous casing of the hole below the water table would be essential. This was achieved by jetting in a 2-inch diameter electrical conduit casing. After removing the jetting pipe one of the screen arrangements, shown in Figure 9 for the auger-hole or the piezometer method, was lowered into the conduit, which was then raised to a stop on the $\frac{3}{4}$-inch pipe attached to the screen.

The water table was allowed to stabilize and the static level read from an electrical sounder. With the short 4-inch screen the sounder wire was run in the annular space between the $\frac{3}{4}$-inch pipe and the 2-inch conduit. In the long screen the sounder wire was inside a $\frac{1}{4}$-inch diameter pipe. The $\frac{1}{4}$-inch pipe was included in the long-screen equipment since it enabled the water level to be lowered almost to the bottom of the screen. This was felt to be unnecessary with the short screen. Apart from this, installation and measurement techniques for both methods are identical. The rate at which the water level builds up is timed and the hydraulic conductivity determined from equations derived by *Kirkham* [1948, 1949], allowance being made for the screen and pipe volumes.

Hydraulic-conductivity measurements were made with this equipment at Sites 1 and 2 and later at Sites 4 and 5. At Site 3, the water table was not high enough above the tile line to allow a comparison with the other tile systems. Results are shown in Table 2.

Now it is reasonable to assume that, other conditions remaining the same, the rate of drop of the water table at the midpoint will vary directly as the hydraulic conductivity K, and inversely as the drainable pore space f. Comparison of the last two columns of Table 3 clearly indicates that the field measurements fail to support this assumption.

In most aspects, all four sites are comparable. Each spacing is 200 ft. Drainable pore space f has only a limited range of values, even with 100 pct error in measurements. Any error in barrier depth is similarly limited. The major variable of unlimited range is hydraulic conductivity itself. To obtain a reliable value of hydraulic conductivity, a large number of measurements must be made, even in a relatively homogeneous soil. Spot measurements in shallow homogeneous soils, where hydraulic conductivity can be determined down to the barrier layer, may give the desired information with some assurance. The Oxnard soils, somewhat typical of the deep alluviums of southwestern United States requiring deep drainage, are far from homogeneous below the tile drains. They tend to be characterized by discontinuous stratification and marked anisotropic properties. *Van Deemter* [1950] has indicated that for soils with no effective barrier layer in the profile, the majority of the flow occurs in a region of depth S/4 where S is tile line spacing. It is quite impractical to obtain hydraulic conductivity of soil to 50 ft depth (S/4 for the common 200-ft spacing). Even with elaborate field equipment and power tools, as used in this work, field determinations by a few spot tests are prohibitive in cost, and clearly a great number of such tests would be required for significant results. Spot methods for hydraulic-conductivity determinations obviously have no merit here. The eventual resolution of this problem may come from the application of geophysical techniques. For the immediate future, a solution based on the recession rate midway between two widely spaced tile drains appears to hold some promise.

To attempt to correlate the recession rate with hydraulic conductivity and clay depth would involve an extensive field program. Preliminary investigations at various points indicated that neither visual inspection nor mechanical analysis were satisfactory to establish accurately the depth of an impermeable barrier. Moreover, the number of hydraulic conductivity measurements would be prohibitively large to attain even a fair degree of accuracy. Additional work using a mathematical model to investigate the relationship between the rate of recession and the parameters influencing this rate is in progress.

Acknowledgments—This research was a part of Project H-1539 LA. The authors wish to express their appreciation to Robert E. Pelishek for his able assistance in carrying out the field program.

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On the Measurement of the Thermal Conductivities of Rocks by Observations on a Divided Bar Apparatus

ALAN E. BECK AND JULIA M. BECK

Abstract—Rapid techniques for the preparation of disks of rock and for the determination of rock conductivities have been used to make a large number of measurements on both coarse-grained and fine-grained rocks. Methods in which either sets of disks or single disks can be used are described and the mean values of conductivity found by combining the results in various ways are compared. The modes of the rocks were found by examination of thin sections for the fine-grained rocks and by examination of each disk for the coarse-grained rocks. Conductivities computed from the modes by the method of Birch and Clark are compared with the experimentally determined conductivities. The significance of rock structure in the selection of representative specimens and the effect of moisture content in porous rocks is discussed. The work indicates that, at least for the coarse-grained rocks, the usefulness of the conductivities obtained from divided bar measurements can be seriously questioned, and that the usual methods of saturating porous rocks are not wholly satisfactory.

Introduction—There is a steadily increasing interest in the flow of heat from the crust of the Earth, both from the land masses and from the bottoms of the oceans. It is the belief of the authors that the greatest need in this work is for a large number of results from all over the Earth. If these results are plotted on a world map and lines of equal heat flux, better described as isoflux lines, are drawn, a general picture of the pattern of terrestrial heat flow may appear.

In any area the calculation of the flow of heat requires a knowledge of the local temperature gradient in the crust and of the thermal conductivity of the rocks in the region; the measurement of the temperature gradient by electrical methods is reasonably rapid and straight forward, but most of the methods of determining the conductivity of rocks involve tedious and complicated procedures. It is the object of this paper to show how it is possible, with suitable apparatus and techniques, to increase the speed and accuracy with which conductivities can be determined and to underline some of the difficulties which up to now appear to have been too lightly treated.

A divided-bar apparatus, capable of reaching the steady state within ten minutes of a specimen being introduced between the bars, was used to find the conductivities of the rocks; a detailed description of the apparatus has been given elsewhere [*Beck*, 1957]. Briefly, however, the method consists of introducing a disk of rock between two vertical cylindrical brass bars; the top end of the upper bar is heated with water controlled thermostatically at 36°C while the bottom end of the lower bar is cooled with water controlled thermostatically at 19°C. The thermal conductivity of the specimen is determined in terms of the conductivity of the bars from temperature measurements made along the bars after the steady state has been reached. The thermal contact resistance between the bars and the specimen is found and eliminated by measurements with three or more disks of different thicknesses. Details of a new method of rapidly cutting off disks of rock will be published elsewhere.

Throughout the paper the units are cgs, °C, and cal except where otherwise stated.

Descriptions of specimens—The scientific value of measured conductivities of rocks is greatly increased if they are accompanied by a statement of their mineral composition and structural features. Furthermore, a knowledge of the quantitative composition is valuable since a theoretical value of the thermal conductivity of the rock may be calculated from it. This method of determining the conductivity is discussed in later sections of the paper and results are compared with those obtained from laboratory methods.

Table 1 lists the mineral composition of rocks from three boreholes in the Snowy Mountains area of New South Wales, Australia. The mode of fine-grained rocks was found by the usual method of examining slides with the aid of an integrating stage. For coarse-grained rocks, in which the conductivity of contiguous disks may differ by as much as 50 pct, it was necessary to find the mode of each disk since the mode of a slide, although more accurately determined, may bear little relation to the mode of the disk. The disk was examined under a binocular microscope with a 100 square

TABLE 1 – *Mineral composition of the rocks, in per cent*

Hole	Depth	Specimen	Composition													
			Quartz	Felspars	Biotite	Chlorite	Muscovite	Plagioclase	Orthoclase	Calcite	Hornblende	Magnetite	Augite	Epidote	Topaz	Interstitial Sericite, Carbonates, etc.
	ft															
1	25	S	32.8		7.9	5.8	0.8	37.7	14.7					0.1		0.2
	38	9	28.2	65.4	6.4											
		10	24.5	55.0	20.5											
		11	37.6	55.0	7.4											
		12	30.7	60.4	8.9											
	48	13	17.0	76.1	6.9											
		14	18.7	79.3	2.0											
		15	28.7	56.6	14.7											
	100	16	31.3	59.4	9.3											
		17	35.6	50.5	13.9											
		18	22.3	63.4	14.3											
		19	25.2	60.0	14.8											
		20	38.3	44.1	17.6											
		21	34.7	45.0	20.3											
		22	28.6	48.4	23.0											
		23	33.0	50.7	16.3											
	142	S	32.1	57.2		1.4	9.3									
		28	30.8	59.1	10.1											
		29	19.8	66.2	14.0											
		30	26.7	60.0	13.3											
	149	31	33.0	53.7	13.3											
		32	25.2	59.3	15.5											
		33	32.5	48.6	18.9											
		34	35.8	52.0	12.2											
	198	35	51.2	46.1	2.7											
		36	38.5	53.9	7.6											
		37	35.4	51.5	13.1											
		38	37.0	54.1	8.9											
	249	39	32.6	53.4	14.0											
		40	36.2	50.0	13.8											
		41	39.6	46.3	14.1											
		42	29.7	53.7	16.6											
		S	28.0		12.5			25.3	34.2							
	295	43	18.0	54.3	27.7											
		44	32.6	49.1	18.3											
		45	15.1	67.5	17.4											
		46	30.5	59.8	9.7											
	345	47	29.9	61.8	8.3											
		48	42.5	50.3	7.2											
		49	29.0	56.4	14.6											
		50A	35.6	49.2	15.2											
		50B	28.8	55.6	15.6											
	350	S	37.6		4.5		5.4	18.2	34.3							
	398	S	36.0		25.1			29.0	9.9							
	399	59	40.5	51.1	8.4											
		60	24.2	62.4	13.4											
		61	29.5	54.9	15.6											
		62	26.0	55.5	18.5											
		63	27.3	62.0	10.7											
		64	27.0	62.9	10.1											
	465	65	33.3	57.7	9.0											
		66	37.2	46.4	16.4											
		67	34.5	53.8	11.7											
		68	24.6	63.9	11.5											

TABLE 1 – *Continued*

Hole	Depth	Specimen	Compositon													
			Quartz	Felspars	Biotite	Chlorite	Muscovite	Plagioclase	Orthoclase	Calcite	Hornblende	Magnetite	Augite	Epidote	Topaz	Interstitial Sericite, Carbonates, etc.
	ft															
2	90	S	13.0		9.8			46.8	3.6		20.4		3.6			2.8
	135	S	15.8		5.8			43.8	4.3		20.6		1.2	6.7		1.8
	170	S_1	9.7		13.2			46.1	7.6		11.9		8.8			2.7
		S_2	7.6		11.5			52.4	7.4		9.5		9.0			2.6
	248	S	11.6		7.8			46.2	2.1		13.2		13.6	4.1		1.4
	290	S	5.6		8.4			56.3	3.7		18.5		5.0			2.5
	428	S	7.8		3.0			43.8			12.3		19.3	13.4		0.4
	470	S_1	13.9		10.8			44.9	4.4		17.4		5.2	0.9		2.5
		S_2	1.6		6.5			37.5	21.9		27.2	0.9	3.3			1.1
3	94	S^a	1.0			50.0				45.0		4.0				
	120	10	44.3	53.2	2.5											
		S^a	43.0	55.0	2.0											
	174	S^a	10.0	60.0		10.0				10.0		10.0				
	248	S^a	45.0		10.0		30.0	5.0		5.0					5.0	
	394	S^a	40.0		10.0		10.0	10.0	30.0						<1.0	

S—Mineral composition was determined from a slide.

[a] Mineral composition was only estimated under a microscope; all other compositions were accurately determined.

grid in one eyepiece and, for each major mineral, measurements were made of the total length of intercept along parallel lines of the grid; this was done for both sides of the disk and the mean taken. The area of observation corresponded with the area enclosed within the guard ring of the divided bar apparatus [*Beck*, 1957]. By coating the surface of the disk with oil, felspar, mica, and quartz could usually be readily differentiated, though in places where the felspar was fresh, difficulty was experienced in detecting the junction between quartz and felspar. To estimate the error in computed conductivities likely to arise from this cause a troublesome specimen (50 from Hole 1) was measured twice. In one case all the doubtful material was classed as felspar and in the other case it was classed as quartz; the resultant difference in computed conductivity was 10 pct. Both values are shown in Tables 1 and 2.

The compositions of rocks from Hole 3, as shown in Table 1, are only approximate. Many of these rocks are very fine grained and altered and the mode was estimated from the examination of slides without making any systematic measurements. Clearly the conductivities computed from these figures are less reliable than those calculated for rocks from the other holes.

Hole 1—In hand specimen it was only possible to divide the rocks from this hole into aplites, which were recorded in the drillers' logs as dykes, and granites which appeared to be very uniform. However, in thin section it was found that some of the rocks described as aplites contained significant amounts of biotite and therefore could be more accurately called microgranites and microgranodiorites; the coarse-grained rocks showed distinct variations in the proportions of quartz, orthoclase, and plagioclase and so could be divided into granites, adamellites, granodiorites and quartz monzonites. These distinctions, based mainly on relative amounts of orthoclase and plagioclase which have very similar thermal conductivities [*Birch* and *Clark*, 1940], would have little effect on the conductivity of the rock and therefore are not shown in Table 2.

Hole 2—This hole passed mainly through fine-grained quartz diorites; in places lamprophyres, presumably forming dykes, and xenoliths of porphyrite were intersected. In Table 2 the grain size refers to the original size of the primary minerals; it is always much greater than the present average grain size of the rock because in most specimens more than half the plagioclase has been strongly saussuritised and the biotite and hornblende have been partly altered to chlorite.

Hole 3—Fine-grained granites, dolerites, and

Table 2 – *Comparison of conductivities obtained from sets of disks and from single disks*

Hole	Depth	Set of Disks		Single Disks					Rock type[a] and general remarks
		Thermal conductivity	Standard devn.	Spec.	Thickness	Thermal conductivity			
						Observed	Computed		
							Disk	Slide	
	ft	cal/cm sec °C	pct		mm	cal/cm sec °C	cal/cm sec °C	cal/cm sec °C	
1	25	0.0069	2.7	1	2.0	0.0076			Microgranodiorite
				2	4.0	0.0072		0.0088[b]	Average grain size, 0.5 mm
				3	7.5	0.0073		0.0062$_a$[b]	Maximum grain size, 3.0 mm
				4	9.0	0.0070			
	35	0.0075	3.6	5	2.0	0.0071			Porphyritic fine grained granite; LSX
				6	4.0	0.0073			MSX
				7	6.0	0.0076			SSX
				8	8.0	0.0073			MSX
	38	0.0090	12.1	9	2.0	0.0083	0.0081[b]		Coarse-grained granite
				10	4.0	0.0076	0.0079[b]		Average grain size, 1.5 mm
				11	6.0	0.0091	0.0093[b]		
				12	7.0	0.0085	0.0085[b]		
	48	0.0084	2.5	13	7.5	0.0078	0.0067[b]		Coarse-grained granite
				14	8.0	0.0079	0.0069[b]		Average grain size, 2 mm
				15	12.5	0.0080	0.0083[b]		
	100	0.0075	5.3	16	2.5	0.0081	0.0086[b]		Coarse-grained granite
		(Specimens 16 to 19)		17	4.5	0.0085	0.0092[b]		Average grain size, 2 mm
		0.0081	7.4	18	6.0	0.0082	0.0075[b]		
		(Specimens 20 to 23)		19	8.0	0.0077	0.0079[b]		
		0.0074	0.1	20	2.5	0.0085	0.0096[b]		
		(Specimens 20 to 22)		21	3.5	0.0081	0.0091[b]		
		0.0079	4.1	22	7.0	0.0077	0.0084[b]		
		(Specimens 16 to 23)		23	8.0	0.0085	0.0089[b]		
	142	0.0079	0.9	24	1.5	0.0080		0.0085[b]	Aplite
				25	4.0	0.0081		0.0059$_a$[b]	Average grain size, 0.4 mm
				26	6.0	0.0080			Maximum grain size, 0.8 mm
				27	7.0	0.0079			*Note:* These specimens and specimens 28–30 were cut from either side of a well marked contact
	142	0.0079	1.3	28	2.0	0.0094	0.0085[b]		Coarse-grained granite
				29	4.0	0.0084	0.0072[b]		Average grain size, 1.5 mm
				30	8.0	0.0082	0.0080[b]		
	149	0.0101	16.9	31	2.5	0.0085	0.0088[b]		Coarse-grained granite
				32	4.0	0.0079	0.0079[b]		Average grain size, 2 mm
				33	5.5	0.0097	0.0088[b]		
				34	6.5	0.0090	0.0092[b]		
	198	0.0081	2.5	35	2.0	0.0107	0.0109[b]		Coarse-grained granite
				36	4.0	0.0093	0.0094[b]		Average grain size, 1.5 mm
				37	5.5	0.0092	0.0091[b]		
				38	7.5	0.0086	0.0093[b]		
	249	0.0085	1.3	39	2.0	0.0090	0.0088[b]	0.0082[b]	Coarse-grained granite
				40	4.0	0.0085	0.0092[b]		Average grain size, 1.5 mm
				41	6.0	0.0086	0.0097[b]		
				42	8.0	0.0086	0.0085[b]		
	295	0.0089	26.2	43	2.0	0.0072	0.0072[b]		Coarse-grained granite
				44	4.0	0.0092	0.0088[b]		Average grain size, 1.5 mm
				45	6.0	0.0066	0.0066[b]		
				46	8.5	0.0090	0.0085[b]		

TABLE 2 – *Continued*

Hole	Depth	Set of Disks		Single Disks					Rock type[a] and general remarks
						Thermal conductivity			
							Computed		
		Thermal conductivity	Standard devn.	Spec.	Thickness	Observed	Disk	Slide	
	ft	cal/cm sec °C	pct		mm	cal/cm sec °C	cal/cm sec °C	cal/cm sec °C	
	345	0.0082	4.7	47	2.0	0.0094	0.0084[b]		Coarse-grained granite
				48	4.0	0.0099	0.0099[b]		Average grain size, 1.5 mm
				49	5.0	0.0088	0.0083[b]		
				50A	8.5	0.0086	0.0092[b]		Doubtful material classified as quartz
				50B	8.5	0.0086	0.0083[b]		Doubtful material classified as felspar
	350	0.0075	0.6	51	2.5	0.0079		0.0093[b]	Porphyritic microgranite.
				52	4.0	0.0078		0.0063_{a}[b]	Average grain size of groundmass, 0.4 mm
				53	6.0	0.0077			Average size of phenocrysts, 1.3 mm
				54	8.0	0.0076			
	398	0.0074	1.3	55	2.0	0.0079		0.0094[b]	Porphyritic microgranodiorite.
				56	4.0	0.0079		0.0067_{a}[b]	Average grain size of groundmass, 0.2 mm
				57	6.0	0.0077			Average size of phenocrysts, 1.5 mm
				58	8.0	0.0076			
	399	0.0079	2.8	59	2.0	0.0103	0.0097[b]		Coarse-grained granite
				60	4.0	0.0079	0.0077[b]		Average grain size, 1.5 mm
				61	6.0	0.0086	0.0084[b]		
				62	8.0	0.0083	0.0080[b]		
				63	9.5	0.0083	0.0081[b]		
				64	11.5	0.0080	0.0080[b]		
	465	0.0082	11.5	65	2.0	0.0082	0.0088[b]		Coarse-grained granite
				66	4.0	0.0089	0.0094[b]		Average grain size, 1.5 mm
				67	6.0	0.0095	0.0090[b]		
				68	8.0	0.0080	0.0077[b]		
2	90	0.0064	8.7	1	2.0	0.0064		0.0061_{a}[b]	Quartz diorite
				2	2.0	0.0060			Average grain size, 0.5 mm
				3	4.0	0.0070			
				4	6.0	0.0063			
	135	0.0065	0.1	5	2.5	0.0064		0.0062_{a}[b]	Quartz diorite
				6	4.0	0.0065			Average grain size, 0.5 mm
				7	6.0	0.0065			
	140	0.0076	1.2	8	2.0	0.0075			Hornblende lamprophyre
				9	4.0	0.0075			
				10	6.0	0.0076			
	170	0.0058	0.0	11	2.0	0.0060		0.0058_{a1}[b]	Quartz diorite
				12	4.0	0.0059		0.0056_{a2}[b]	Average grain size, 0.4 mm
				13	5.5	0.0058			
	177	0.0071	0.6	14	2.0	0.0070			Augite hornblende lamprophyre
				15	4.0	0.0071			
				16	6.0	0.0071			
	198	0.0072	1.2	17	2.0	0.0076			Augite hornblende lamprophyre
				18	4.0	0.0075			
				19	6.0	0.0073			
	248	0.0066	1.2	20	2.0	0.0069		0.0077[b]	Porphyritic quartz diorite
				21	4.0	0.0068		0.0062_{a}[b]	Average grain size of groundmass, 0.5 mm
				22	5.5	0.0067			Average size of phenocrysts, 3.0 mm
	290	0.0055	1.3	23	2.0	0.0057		0.0056_{a}[b]	Porphyritic quartz diorite
				24	4.0	0.0056			Average grain size of groundmass, 0.3 mm
				25	6.0	0.0056			Average size of phenocrysts, 2.5 mm

TABLE 2 – *Continued*

Hole	Depth	Set of Disks		Single Disks					Rock type[a] and general remarks
						Thermal conductivity			
		Thermal conductivity	Standard devn.	Spec.	Thickness	Observed	Computed		
							Disk	Slide	
	ft	cal/cm sec °C	pct		mm	cal/cm sec °C	cal/cm sec °C	cal/cm sec °C	
	329	0.0065	5.2	26	2.0	0.0064			Mica lamprophyre
				27	4.0	0.0062			
				28	5.5	0.0065			
	409	0.0055	1.0	29	2.0	0.0056			Mica porphyrite
				30	4.0	0.0057			
				31	7.5	0.0056			
	428	0.0061	0.9	32	2.0	0.0061		0.0062_{s}[b]	Quartz diorite
				33	4.0	0.0061			Average grain size, 0.5 mm
				34	6.0	0.0061			
	470	0.0064	1.5	35	2.0	0.0063		0.0061_{s1}[b]	Porphyritic quartz diorite.
				36	4.0	0.0062			Average grain size of groundmass, 0 4 mm
				37	5.0	0.0062		0.0057_{s2}[b]	Average size of phenocryst. 2 mm
				38	8.0	0.0064			
3	23	0.0069	1.2	1	2.0	0.0080			Porphyritic microgranite
				2	3.5	0.0077			
				3	5.0	0.0074			
				4	7.5	0.0072			
	94	0.0058	0.7	5	1.5	0.0050		0.0073[c]	Sheared dolerite (slightly weathered)
				6	6.0	0.0056		0.0071_{s}[c]	Average grain size, 0.05 mm
				7	8.0	0.0056			
	120	0.0078	2.5	8	4.0	0.0084		0.0099[c]	Sheared porphyritic microgranite
				9	6.5	0.0083		0.0066_{s}[c]	Average grain size of groundmass, 0.3 mm
				10	8.5	0.0080	0.0101[b]		Average size of phenocryst, 3 mm
	174	0.0085	1.8	11	1.5	0.0080		0.0067[c]	Sheared dolerite
				12	3.5	0.0081			Average grain size, 0.5 mm
				13	5.0	0.0080			
				14	9.0	0.0084			
	182			15	3.0	0.0041			Dolerite (moderately weathered)
	248	0.0096	10.7	16	2.0	0.0099		0.0107[c]	Greisenised fine-grained granite
		(Specimens 16 to 19)		17	4.0	0.0092			Average grain size, 1 mm
		0.0079	6.7	18	5.5	0.0085			
		(Specimens 16 to 18)		19	8.5	0.0098			
		0.0098	5.0						
		(Specimens 16, 17, 19)							
	394	0.0077	6.4	20	2.0	0.0083		0.0097[c]	Partly greisenised fine-grained granite
		(Specimens 20 to 23)		21	3.5	0.0081		0.0066_{s}[c]	Average grain size, 1 mm
		0.0075	0.9	22	6.0	0.0085			
		(Specimens 20 to 22)		23	7.5	0.0077			

LSX Large section of biotite xenolith through specimen.
MMX Medium section of biotite xenolith through specimen.
SSX Small section of biotite xenolith through specimen.
[a] Rocks named from examination of slides and reference to drillers logs.
[b] Indicates that mineral composition has been accurately determined and is given in Table 1.
[c] Indicates that mineral composition has only been estimated and is given in Table 1.
Subscript s denotes conductivity computed assuming a series arrangement of minerals; all other computed conductivities are found assuming a parallel arrangement of minerals; 1 and 2 are different thin sections of the same rock.

porphyritic microgranites were intersected by this borehole. As noted earlier most of them have been altered, either by weathering, shearing, or pneumatolysis, including strong greisenisation, and their compositions have been determined only approximately.

Conductivities obtained from sets of three or more disks—Between the faces of the specimens and the bars of any divided bar apparatus there is a thermal contact resistance which is found and eliminated by measurements on three or more disks of different thicknesses cut from the same rock. To do this the total thermal resistance, including the contact resistance, of each specimen is plotted against its thickness D in cm. A straight line is obtained of the form

$$\Theta \Big/ \frac{d\theta}{dx} = B + \frac{k_1}{k_2} D \qquad (1)$$

where Θ is the temperature difference between the two faces of the brass bars, $\frac{d\theta}{dx}$ is the temperature gradient in the brass bars, B is the sum of the thermal resistances of the two interface films and k_1 and k_2 are the conductivities of the brass and rock respectively. If the conductivity of the brass is known the conductivity of the rock can be found from the slope of the line; the intercept at $D = 0$ will give the contact resistance B. In this work the equation of the straight line and the standard deviation of its slope have been found from the least squares theory.

The conductivities of sets of specimens from three boreholes are shown in the third column of Table 2. When a set of disks gave a value of conductivity with a standard deviation greater than 3 pct the complete set was measured again. In no case did the second value for the total thermal resistance of an individual disk depart from the original value by more than 1 pct and the standard deviation of the set did not change by more than 0.6 pct; the comparatively large standard deviations of many of the sets of disks therefore indicate real variations of conductivity from disk to disk.

Errors which may arise when the thermal conductivity is derived from a set of disks are demonstrated by omitting certain disks from the set and calculating a new least-squares straight line through the thermal resistance-thickness points; it can be seen (Hole 1, 100 ft; Hole 3, 248 ft) that markedly different values for the conductivity can be obtained. In another case (Hole 3, 394 ft) the conductivity is not significantly altered but a completely erroneous idea of the accuracy is obtained.

The use of single disks—With a little skill extremely uniform disks can be produced; it might therefore be hoped that, at least when a liquid contact film is used, the contact resistance would vary so little from disk to disk that a standard contact resistance could be found for a given instrument and tolerances of rock machining. This resistance could then be used with a single disk to give a measurement of conductivity. This practice would have the effect of decreasing to at most one third the time involved in preparing specimens; it would also be of great advantage with the many friable and broken rocks from which it is not possible to get a set of three disks, and with other rocks, particularly with some schists, from which it is frequently impossible to cut thin disks at all. A further disadvantage of the standard procedure when applied to coarse grained rocks will appear below.

To determine whether it was possible to use a standard resistance a histogram (see Fig. 1) was plotted of all contact resistances obtained. This histogram has a mode at about 0.5 cm brass and includes the many aberrant values, both negative and high positive, which were measured. (It is convenient in practice to express contact resistance in cm of brass. This unit is used throughout this work. To convert to the usual units, sec cm °C/cal, multiply by 4.3.) These, which have been noted elsewhere [*Bullard*, 1939], occur in coarse-grained rocks in which the normal laboratory disks are not representative of the rock as a whole, and are brought about by a scatter of points when the total thermal resistance is plotted against the disk thickness. This scatter of points, which indicates a difference in thermal resistance per unit thickness, is due to (1) the high probability of finding, from disk to disk, a variation in the proportions of the constituent minerals; and (2) an increasing probability, as the disk thickness increases, of the disk having a 'series' arrangement of minerals. The question of 'series' and 'parallel' arrangements of minerals is discussed subsequently.

To obtain a more accurate standard contact re-

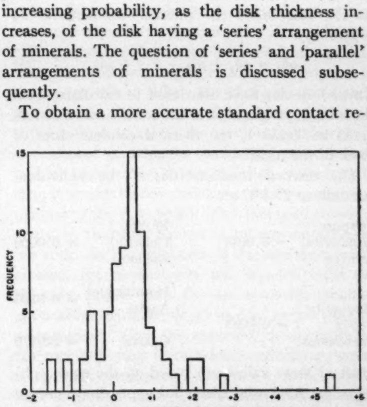

FIG. 1 – Histogram of contact resistances for 82 sets of disks

sistance only those lines of positive intercept and with a standard deviation of 1.5 pct or less were used; this effectively sets a limit on the curvature caused by the effects mentioned above. The mean value found by this method was 0.49 cm ± 12.2 pct. Since the average thermal resistance of a disk of rock 2 mm thick was about ten times the contact resistance (that is, from Eq. (1), $0.2\ k_1/k_2 \approx 10\ B$) an error of 20 pct in the contact resistance will give only 2 pct error in the thermal resistance of the 2 mm disk and less for the thicker ones. The conductivities found by subtraction of the standard contact resistance from the measured total resistance of each disk are shown in the seventh column of Table 2. The thickness of the specimens is given to the nearest 0.5 mm. The figures in the columns marked 'computed' are based on the mineral compositions given in Table 1 and are discussed in the following sections.

Thermal conductivity computed from the volume percentage of the constituent minerals—The idea of 'series' or 'parallel' arrangements of minerals was introduced by *Birch* and *Clark* [1940]; it is developed later but it may briefly be stated here that if a rock consists of n minerals with α parts of a mineral of conductivity k_a, β parts of a mineral of conductivity k_b, $\cdots$, η parts of a mineral of conductivity k_n, then its 'series' conductivity k_s is given by

$$\frac{n}{k_s} = \frac{\alpha}{k_a} + \frac{\beta}{k_b} + \cdots + \frac{\eta}{k_r} \qquad (2)$$

on the other hand the 'parallel' conductivity k_p is given by

$$nk_p = \alpha k_a + \beta k_b + \cdots + \eta k_n \qquad (3)$$

These formulas have been used to calculate, from the volume proportions of the constituent minerals given in Table 1, the thermal conductivities of some of the rocks.

The thermal conductivities of the individual minerals at 27.5°C are

$$\left.\begin{array}{l}\text{Felspars}\\ \text{Muscovite}\\ \text{Sericite}\end{array}\right\} = 0.0045 \qquad \left.\begin{array}{l}\text{Biotite}\\ \text{Chlorite}\\ \text{Epidote}\end{array}\right\} = 0.0060$$

$$\left.\begin{array}{l}\text{Hornblende}\\ \text{Augite}\end{array}\right\} = 0.0100$$

$$\left.\begin{array}{l}\text{Magnetite}\\ \text{Topaz}\\ \text{Carbonates}\end{array}\right\} = 0.0085 \qquad \text{Quartz} = 0.0170$$

Most of these values are based on the work published by Birch and Clark but approximations are used in those cases for which they give no definite figure. In this respect, the only mineral of any significance is biotite. Birch and Clark did not measure the conductivity but tentatively estimated its value as 0.01. However, in many of the rocks used in the present work some of the biotite has been altered to chlorite the conductivity of which is 0.0060 [*Mossop* and *Gafner*, 1951]; the type of replacement and the broadly similar structure of the two minerals suggested that a fairer picture would be given by assigning this value to the biotite. The fact that the conductivity of specimens from the 35-ft level of Hole 1 decreases as the volume occupied by the biotite xenolith increases, supports the validity of this lower value.

The results of the computations are shown in the eighth and ninth columns of Table 2. The values with the subscript s are the series conductivities; the others are the parallel conductivities. The values in the eighth column were obtained from measurements on the actual disks used while the figures in the ninth column were derived from the mode of the slide.

Mean value of thermal conductivity—Comparison of the figures in the third and seventh columns of Table 2 shows up the limitations of the method of using three or more disks in the divided-bar apparatus. In particular it may be noted that conductivities of 0.0075 and 0.0081 were obtained from two separate sets of disks cut from the core from the 100-ft level of Hole 1. More than 450 ft of this hole passes through granite of very uniform composition but the measured values of the thermal conductivity of individual disks range from 0.0066 to 0.0107 (col. 7, Table 2). These variations are brought about by the reasons given in the section on single disks and are most probably fluctuations about a mean. There were 48 disks of this granite and it is worth while, therefore, comparing values of the mean conductivity obtained from the procedures described in the previous sections. The four main methods of treating the data are as follows:

(1) Using the values derived from sets of three or more disks.

(2) Plotting on one graph all total resistances against thickness, regardless of depth, and calculating the least-squares straight line for all points (Fig. 2). When this was done and the residuals (observed resistance − calculated resistance) were arranged in order of depth it was noticed that the majority of the residuals from 0 to 142 ft. were positive while below this the majority were negative. As this indicates a difference in thermal conductivity the points were divided into ranges and two new straight lines determined.

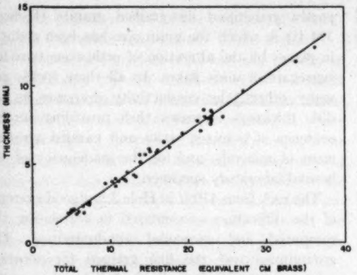

FIG. 2 – Least-squares straight line through points for 48 disks of a fresh coarse-grained granite

(3) Using the values obtained by determining a value for the thermal conductivity of each disk assuming a standard contact resistance of 0.49 cm of brass.

(4) Using the computed parallel conductivity of each disk.

The results from these methods are compared in Table 3; standard deviations are also shown.

TABLE 3 – *Mean values for conductivity of coarse-grained granites in Hole 1*

Method	Remarks	Conductivity
		cal/cm sec °C
1a	Unweighted mean from straight lines	0.0083 ± 3.4 pct
b	Weighted mean [*Birge*, 1932] from straight lines	0.0082 ± 1.1 pct
2a	Plotting all total resistances against thickness	0.0080 ± 2.1 pct
b	Dividing into two ranges	
	0 to 142 ft.	0.0079 ± 2.4 pct
	142 to 465 ft.	0.0082 ± 3.6 pct
3a	Subtracting contact resistance of 0.49 cm brass from the total resistance	0.0086 ± 1.3 pct
b	Dividing into two ranges	
	0 to 142 ft.	0.0083 ± 1.3 pct
	142 to 465 ft.	0.0088 ± 1.7 pct
4a	Computed conductivity for all specimens	0.0085 ± 1.8 pct
b	Dividing into two ranges	
	0 to 142 ft.	0.0083 ± 2.3 pct
	142 to 465 ft.	0.0087 ± 1.4 pct

For some of the disks the computed conductivity assuming a parallel arrangement of minerals differs appreciably from the measured conductivity Table 2, but the errors (observed value – computed value) follow a normal distribution, and arise almost entirely from difficulties in accurately determining the mineral composition.

Comparison of Method 3 with Methods 1 and 2 shows that significantly different values of the mean conductivity can be obtained according to which approach is used; because the value of 1a has a much higher standard deviation than that of 3a the difference between the two values is not very significant.

Since many of the straight lines used in Methods 1 and 2 had a negative contact resistance, Method 3 is clearly superior. Some support for the accuracy of the values found by Method 3 is given by the good agreement of these values with those found for the computed conductivity, Method 4, over the corresponding ranges of depths.

The significance of rock structure in the selection of representative specimens—The results in Table 2 show that for many coarse-grained rocks the normal laboratory specimen is too small to represent a large mass of the rock: even the thickest disks of coarse-grained granite appear to have the minerals arranged in parallel. It is therefore necessary to understand which structural features of a rock affect the probability of its minerals showing a series arrangement in laboratory specimens and so to establish some working relationship between the grain size and the minimum thickness required to give the 'bulk' or *in situ* conductivity.

Most rocks contain monomineral chains or aggregates which can cause an apparent increase in thermal conductivity; similar effects are caused by the presence of phenocrysts.

If it is assumed that the monomineral chains are perpendicular to the faces of a disk, a laboratory specimen will give the bulk conductivity only when its thickness is greater than the length *l* of the longest chain. When the thickness of a disk is just less than *l* at least one of the chains of minerals will run directly across the specimen; if this chain is composed of a highly conducting mineral, heat will be transmitted across the disk more rapidly than it would if a few grains of a poorly conducting mineral were interposed. The increased conductivity of the disk renders it unrepresentative of the rock. As the thickness of the specimen is decreased, the conductivity will increase until the thickness is less than the size *m* of the smallest grain when the minerals are said to have a parallel arrangement. Thus the apparent conductivity of the rock will vary from a low conductivity equal to the bulk conductivity when the specimen thickness is greater than *l*, to a comparatively high conductivity when the specimen thickness is less than *m*. In practice, the chains of minerals have a great range of lengths and are usually at all angles to the faces of the specimen. Other wide variations in rock texture occur which make a theoretical approach difficult.

The present work suggests that before a disk may definitely be treated as having a series arrangement of minerals, the ratio of the disk thickness D to the average grain size G should be at least 15. This does not preclude the possibility of using specimens with much lower values of D/G provided it is quite certain that there are few monomineral aggregates and that the grain size is very even. In general, however, it seems probable that for specimens in which D/G is less than ten, a computation of thermal conductivity assuming a parallel arrangement of minerals will give results closer to the measured conductivity than a similar calculation assuming a series arrangement. For disks which have a value of D/G lying between 10 and 15 there will be some complicated combination of series and parallel elements which will cause the measured conductivity to lie between the series computed and parallel computed conductivities.

The coarse-grained granites from Hole 1 have been very thoroughly investigated and the conductivities computed from their mineral compositions gave the first clue to the inadequacy of the normal laboratory specimen. It was found that in all the disks, even the thickest ones (no. 15 and 64), the minerals were clearly arranged in parallel: Specimen 15 had a D/G value of 6 and Specimen 64 a D/G value of 8. It had been guessed that all the disks up to 6 mm thick had the minerals arranged in parallel since they were quite transluscent; some of the 8 mm disks were also transluscent but all other disks were opaque.

Many of the slides of the coarse-grained granites showed small xenolithic patches rich in biotite. The effect of the inclusion of a macroscopic xenolith of this composition in the disks from 35 ft has been noted in the section on computed conductivities.

For porphyritic rocks and those with a noticeably uneven grain size the measured conductivity of normal laboratory specimens lies between the series computed and parallel computed conductivity. A typical porphyritic specimen (10 from Hole 3) consists of phenocrysts of quartz, orthoclase, and plagioclase, $D/G = 3$, in a groundmass of the same minerals, $D/G = 28$, in approximately equal amounts. Similar wide differences of D/G values are shown by a microgranodiorite (Hole 1, 25 ft) which has an average grain size of 0.5 mm but contains several grains 3 mm long, and by a partly greisenised fine-grained granite (Hole 3, 394 ft) in which the grain size has been reduced in places by the alteration of orthoclase to a fine aggregate of mica flakes. In all these rocks, and many others, the conductivity decreases as the disk thickness increases thus providing further evidence of a mixed series and parallel arrangement of minerals, and for the inadequacy of the normal laboratory specimen.

The rock from 470 ft in Hole 2 is a good example of the difficulties encountered in correlating the computed and measured conductivities. The groundmass was too fine grained for accurate measurements on the individual disks whereas the two slides showed differences in composition due to the porphyritic texture of the rock.

In the even-grained diorites from Hole 2 it appears that the minerals are dominantly arranged in series. The alteration in the rocks makes it difficult to determine accurately the average grain size and hence to obtain reliable maximum and minimum values of D/G, but using the original grain size of the primary minerals these values are 12 and 4; allowing for the alteration, it is estimated that the values are 30 and 10.

It is doubtful if it will ever be possible to predict the exact thickness required in the general case of a rock containing more than one mineral. However, experience with these rocks has shown that a thin section should be examined before disks are cut.

The effect of moisture content on porous rocks—In the past, investigations into the variation of thermal conductivity with changes in water content of a porous rock have been hampered either by the use of steady-state apparatus with long time lags or by the use of transient methods; both methods lead to a non-static distribution of moisture in the specimens. The divided bars used in the present work have considerably reduced the time lag difficulties.

Three types of rock were investigated but only one will be discussed in detail in this paper. This rock was a porous sandy shale obtained from an outcrop instead of from a borehole as were the rest of the rocks. Cores were drilled parallel and perpendicular to the bedding and coated with a layer of waterproof plastic paint. Attempts to drill at various angles to the bedding resulted in complete failure because of splitting along the planes when either the cores or disks were being prepared. Ten disks were cut from the core drilled perpendicular to the bedding and five disks were cut from the core drilled parallel to the bedding; the thickness of the disks ranged from 1.5 to 8 mm.

For many geophysical problems only the dry or the saturated thermal conductivity of a rock is required but there are numerous fields, for example, building materials and mine ventilation, where a knowledge of heat losses through damp porous media is required. The thermal conductivity of each set of disks was therefore determined for the saturated state, and for a number of different unsaturated states with dry contacts between the bars and disks. The results for the porous shale are shown in Tables 4 and 5.

In view of the observations by other workers [*Benfield*, 1939; *Clark*, 1941; *Mossop* and *Gafner*, 1951] the results are rather surprising since they show large variations of conductivity with relatively small changes in water content. This point is emphasized by the lines shown in Figure 3 which were obtained using coarse-grained granites. However, for the reasons given in the section on the use of single disks, these results are not regarded as reliable as those for the very fine-grained porous shale.

TABLE 4 – *Variation of thermal conductivity with water content; heat flowing perpendicular to bedding of weathered shale; ten specimens*

Water content by volume pct	Thermal conductivity	Standard deviation
pct	cal/cm sec °C	pct
13.2	0.0082	2.2
8.2	0.0080	2.4
4.6	0.0070	4.9
2.3	0.0064	3.5
0.0	0.0061	3.8

TABLE 5 – *Variation of thermal conductivity with water content; heat flowing parallel to bedding of weathered shale; five specimens*

Water content by volume	Thermal conductivity	Standard deviation
pct	cal/cm sec °C	pct
12.5	0.0079	0.3
8.9	0.0074	0.9
5.7	0.0065	4.4
3.4	0.0062	4.4
1.6	0.0057	3.7
0.0	0.0047	3.3

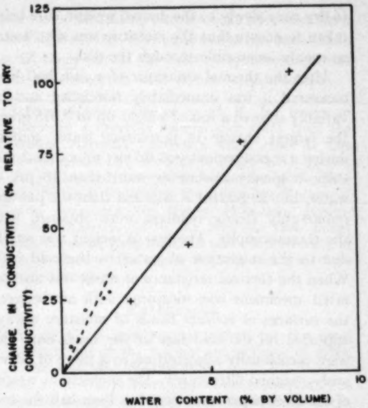

FIG. 3 – Percentage change in conductivity due to increase in water content; the crosses and the full line were obtained with a badly weathered coarse-grained granite; the points and the dashed line were obtained with a slightly weathered coarse-grained granite; in both cases the highest water content was obtained by applying a pressure of 150 lb/in² to all specimens

Each disk was dried to constant weight and the thermal resistance was measured on the guard ring apparatus with dry contacts between the faces of the disk and bars. The disks were then immersed in water at normal room pressure until they reached a constant weight after a few days. The thermal conductivity of each set of disks was found in the usual manner using liquid contacts; each disk was weighed before and after measurement and showed no significant change in weight. Experiments with an extra disk ten mm thick and immersed in water containing a dye indicated that the water penetration of the disks was uniform when saturated at room pressure. However, it was later found that when the rocks were immersed in water at 150 lb/in² they absorbed more water and reached a new saturated constant weight. That this increase in the amount of water taken up was not entirely due to any permanent alteration in the structure of the rock was indicated when the specimens were dried and again soaked to constant weight at normal pressures; the amount of water absorbed, although slightly higher than that first observed, was still less than the amounts taken up under pressure. Vacuum drying and letting the water in at this reduced pressure gave little improvement over the method of soaking in water at room pressures.

The intermediate unsaturated states were obtained by selecting a convenient percentage of water and calculating the weight of each disk necessary to obtain this percentage. After the disk was saturated at normal pressure it was allowed to dry very slowly to the desired weight, care being taken to ensure that the moisture was distributed as evenly as possible through the disk.

After the thermal resistance of a disk had been measured it was immediately reweighed and invariably showed a loss of weight up to 0.015 gram; the largest change in percentage water content during a measurement was 0.7 pct on a disk 2 mm thick originally containing more than 10 pct of water, but in general it was less than 0.2 pct and remarkably steady readings were obtained with the thermocouples. The loss of weight was partly due to the migration of water to the cold face. When the thermal resistance of moist but unsaturated specimens was measured with air between the surfaces of contact beads of moisture always appeared on the cold face of the brass bars and were occasionally absorbed on to a piece of previously weighed filter paper. The increase in weight of the filter paper was never less than half the loss in weight of the specimen; the discrepancies were mainly due to the small quantities of moisture involved although there was probably a slight loss of one or two milligrams when transferring the specimen from the balance to the apparatus and back again. However, because of the waterproof paint round the sides of each specimen, it is doubtful if any water was lost to the atmosphere while the specimen was between the bars. That the migration of water to the cold face was due to a thermal gradient and not due to gravity was shown by reversing the thermostatic baths and heating the lower end and cooling the upper end of the apparatus; when a moist specimen was placed between the bars, beads of moisture appeared on the contact face of the upper cold bar but not on the face of the lower hot bar. When the condensation was first noticed experiments were made with greased surfaces to prevent the water getting out of the disk. Unfortunately, the grease was found to soak into the surfaces and it could not be removed even when the specimen was boiled in carbon tetrachloride and then benzene.

Complications arose from the fact that in the shales some of the water was undoubtedly adsorbed; this was indicated by micrometer measurements of the disks which showed that they swelled by a few ten thousandths of an inch when saturated. This did not occur in the granites. Experiments with liquids other than water, say an organic liquid or even a low-melting-point solder, would probably give results which could be interpreted more easily, since the problems of adsorbed films of liquid and the transfer of heat by the vapor phase would be considerably reduced. It is surprising that no one appears to have done this when checking a theory of conduction of heat in porous media.

In any of the moist states there is, of course, a possibility of water penetrating the disks in a non-uniform manner even though precautions were taken to prevent this. Fortunately, the standard deviations (Tables 4 and 5) indicate that when a set of disks containing a given percentage of water was measured the average thermal resistance per unit thickness was reasonably constant from disk to disk; these consistent results suggest that either the water penetration was fairly uniform or if it was non-uniform this does not upset the results very much.

There is also a possibility that the migration of water to the cold face may give rise to a variable contact resistance. This probably does occur immediately after the disk is introduced but after five to ten minutes a very steady state is reached, the variation between successive readings of any given thermocouple being no greater than that for impervious rocks. The probable mechanism here is that immediately after the damp disk is placed between the bars, water begins to migrate to the cold face and there condenses. When sufficient moisture has condensed to block up the pores of the cold face of the disk the migration ceases since all exits are blocked either by the condensation at the cold face or by the plastic paint on the outside surface. The condition inside the disk is therefore one of slightly uneven but stable moisture distribution. After the steady state has been reached there is, in effect, one wet contact and one dry contact. Some support for this is given by the values for the resistance of the various films of contact. For the dry disks the contact resistance of each air film was 2.4 cm brass whereas the resistance for each liquid film for the saturated disks was 0.2 cm brass; for the moist specimens the combined resistance of the two contact films was 3.1 cm brass.

The most important state of the rock with regard to crustal heat flow is the saturated state. In saturated or nearly saturated media it is practically impossible to make moisture move down a temperature gradient [*Hutcheon* and *Paxton*, 1952; *Kuzmak* and *Sereda*, 1957] so that the moisture migration problem will not arise in heat flow measurements. However, there is considerable doubt as to when a rock is saturated. The present work has shown that at higher pressures more water can be squeezed into a rock but that it is unlikely that this is due to a permanent alteration in the structure of the rock. The conclusion then, is that at room pressures the rock is not saturated merely by being soaked in a dish of water or by water being let in under vacuum. If the conductivity of a porous rock from depth is required some reliable technique for saturating the rock must be developed.

Discussion—Even if allowances are made for all the difficulties described in the previous sections and for the changes of pressure and temperature when a rock is brought to the surface, there is still a doubt as to whether a specimen is truly representative of the rock *in situ*. Rocks have beed known to shatter completely when they are being cut, implying the presence of internal strains and cracks produced by the removal of pressure ann subsequent working. Since this is a permanent physical change, the reapplication of pressure probably does not completely restore the rock to its original state. An interesting, though somewhat extreme, case of what can happen is given by *Godridge* [1956]; he shows that very light mechanical maltreatment of coal samples results in a 10 to 15 pct reduction in thermal conductivity.

The only way these doubts can be removed is by a systematic investigation over a wide variety of rock types, comparing the laboratory results with an independent method of measuring thermal conductivities *in situ*. If it is known that there are no inconsistencies in the walls of a borehole then a probe technique [*Blackwell*, 1954; *Crowe*, 1956] can be used. However if there are irregularities caused by drilling, then, to increase the depth of penetration of heat and so reduce the effects of irregular walls, it will be necessary to use a technique similar to that tried in Tasmania [*Beck* and others, 1956] where a long length of borehole was heated for a long time.

Conclusions—It has been shown that for a given apparatus and known tolerances of rock machining, rapid and reliable measurements of thermal conductivity can be made on single disks. The results from this method demonstrate that for many coarse-grained rocks the normal laboratory specimens are so small that they give a value of the conductivity significantly higher than the thermal conductivity of a large mass of the rock. This is due to the minerals showing a dominantly parallel instead of a series arrangement. Therefore before disks are cut a thin section of a rock should be examined to determine the average grain size; disks thick enough to be representative of a large mass of the rock can then be prepared. The methods of saturating porous rocks have also been found inadequate. When allowance has been made for all these effects the laboratory measurements must be correlated with *in-situ* measurements.

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Radioactive Ages of Micas from Granitic Rocks by Rb-Sr and K-A Methods

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Abstract—Analytical data and ages are given for K-A, Rb-Sr, U-Pb and Th-Pb ages from a number of locations. Comparisons of the ages obtained indicate (a) that K-A and Rb-Sr ages of mica usually agree when modern laboratory determined values of the decay constants of K^{40} and Rb^{87} are used; (b) that the K-A and Rb-Sr ages of micas agree with the U-Pb ages of cogenetic uraninite, zircon, and monazite when the U-Pb ages are concordant; (c) that when the U-Pb ages of these uranium minerals are discordant, the mica ages agree best with the Pb^{207}-Pb^{206} age; (d) that the pattern of K-A and Rb-Sr ages of micas can be most simply explained by postulating the loss of variable but small amounts of argon from the mineral.

The usefulness of a reliable method by which either relative or absolute ages of rocks could be measured has long been appreciated. That concordant, and therefore probably reliable, U-Pb ages of pegmatitic uraninites are usually obtained was demonstrated by *Wasserburg* and *Hayden* [1955]. The frequent occurrence of discordant ages of other uranium- and thorium-containing minerals is also well known. This paper presents the results of the continuation of the studies of cogenetic minerals at the Carnegie Institution. In this work the measurements of the K-A and Rb-Sr ages are emphasized. In some cases U-Pb and Th-Pb ages have also been obtained. The comparisons of all radioactive ages have proved to be informative and helpful in the interpretation required to obtain the age of the rock studied. A study of zircons from granites and pegmatites [*Tilton* and others, 1957] is another example of this kind of work.

For nearly a decade it has been possible to measure the argon content of potassium minerals. The results have been summarized by *Wetherill* and others [1956b] who point out that the decay constant λ_e obtained from the measurements of the ratio A^{40}/K^{40} for micas and the concordant U-Pb ages of cogenetic uraninites is in good agreement with that found from laboratory measurements of the decay constants of K^{40} [*Wetherill*, 1957].

The presence of radiogenic Sr^{87} in rubidium minerals has been known for two decades. The measurements of the decay constant of Rb^{87} have been discussed by *Aldrich* and others [1956b]. The empirical determination of the Rb^{87} decay constant from measurements on cogenetic minerals containing uranium and rubidium gives a value for λ_β of $1.39 \pm 0.05 \times 10^{-11}\text{yr}^{-1}$. Because of the difficulties of analysis before 1948, measurements of the ratio Sr^{87}/Rb^{87} were few, and confined to lepidolites where the strontium content of the mica could reasonably be assumed to be entirely radiogenic. Most of these measurements were made by *Ahrens* [1955] and his co-workers by spectrochemical methods. Ahrens pointed out the difficulties of his techniques as had others [*Nicolaysen*, 1954]. As a result, his measurements must be assumed to be semiquantitative in nature. The possibility of determining Rb-Sr ages of biotites was pointed out by *Whiting* [1951] from his spectrochemical determinations of the ratio of strontium to rubidium. The high percentage of radiogenic Sr^{87} in the Sr^{87} of these minerals was confirmed by *Herzog* and others [1953], and *Aldrich* and others [1955].

Laboratory measurements of the decay constant of Rb^{87} have ranged from 1.09 to $1.73 \times 10^{-11}\text{yr}^{-1}$ with the larger number of determinations near 1.15. The difficulty of properly forming and counting the thin sources necessary for the weak (average energy of 45 kilovolts) beta-particles emitted in the decay of Rb^{87} could account for this low value. The recent careful work of Huster and Rausch (private communication) seems to favor an intermediate value for this constant of $\lambda_\beta = 1.39 \times 10^{-11}\text{yr}^{-1}$, which is in excellent agreement with the geologically-determined value found at the Carnegie Institution. This agreement does not remove the need for further laboratory corroboration of the value of the decay constant. The decay constants of K^{40}, Rb^{87}, Th^{232}, U^{235} and U^{238} for the work discussed in this paper are given in Table 1.

Analytical procedures—The analytical procedures are based on the method of isotope dilution and have been described in detail elsewhere

TABLE 1 – *Decay constants and isotopic abundances of radioactive isotopes used in this paper*

Isotope	Decay constants	Isotopic abundance
K^{40}	4.72×10^{-10} yr^{-1} (beta decay) 0.585×10^{-10} yr^{-1} (K-capture)	1.22×10^{-4} g/g K
Rb^{87}	1.39×10^{-11} yr^{-1}	0.283 g/g Rb
Th^{232}	4.99×10^{-11} yr^{-1}	1 g/g Th
U^{235}	9.72×10^{-10} yr^{-1}	0.00711 g/g U
U^{238}	1.54×10^{-10} yr^{-1}	0.9929 g/g U

[*Wetherill* and others, 1956a; *Aldrich* and others, 1956a; *Aldrich*, 1956]. The one simplification which has been made, now that both K and Rb determinations for the same sample are desired, is to add a mixture of K^{41} and Rb^{87} tracer to the same aliquot of the sample. A single mass spectrometer run in which both ratios, K^{39}/K^{41} and Rb^{87}/Rb^{85}, of the solution of the aliquot and the mixed tracer are measured suffices to make these determinations.

The analytical procedure used for the determination of U, Th, and Pb in uraninite has not been presented previously. A uraninite crystal is hand-crushed to −20 mesh, and fresh unaltered portions hand-picked with the aid of a low-power microscope. A 20–50 mg sample is dissolved in a small amount of redistilled nitric acid and then diluted to 100 ml in a volumetric flask. To 200 microliters of this solution is added 1 ml of U^{235} tracer containing 5.93 μg U^{235} and less than 0.005 μg U^{238}, and 0.250 ml of Th^{230} tracer containing 7.14 μg Th^{230} and 0.762 μg Th^{232}. This solution is diluted and heated to equilibrate the U and Th of sample and tracer solutions, and dried. A portion of this mixture is taken up in two drops of 0.1 M HNO_3 and placed on an outgassed tantalum ribbon in the mass spectrometer source. The U analysis is completed by measurement of UO_2^+ ions emitted thermionically from the ribbon. The Th is emitted at considerably higher temperatures as the ThO^+ ion and is readily located by the UO^+ peaks. From the U^{238}/U^{235} and Th^{232}/Th^{230} ratios the U and Th concentrations of the dissolved sample are calculated.

Two analyses are required to determine the isotopic composition and concentration of the Pb in a uraninite. To 2 ml of the uraninite solution is added 20 μg of Pb^{208} tracer solution. The mixture is equilibrated and extracted as the dithizonate complex into chloroform at pH 8.5 in the presence of potassium cyanide and ammonium citrate. Pb is stripped into two per cent HNO_3, and PbS is precipitated from solution at pH 4.5. The PbS is then placed on an outgassed tantalum ribbon and dried with some of the ammonium nitrate solution from which it is precipitated. The lead is analyzed as Pb^+ emitted thermionically from the ribbon in the mass spectrometer source. The procedure above is repeated omitting the Pb^{208} tracer and the isotopic composition of the Pb in the uraninite obtained. From these two analyses the data required to determine the radiogenic Pb^{206}, Pb^{207}, and Pb^{208} content of the uraninite are obtained. The analyses have an error of two per cent in the Pb concentration and one per cent in the isotopic composition of the uraninite leads.

Analytical data—The analytical data are presented in four tables. Unless otherwise indicated the errors of the analytical measurements of concentrations of K, Rb, Sr^{87}, and A^{40} are less than three per cent. Table 2 gives the analytical data for five pegmatites for which K-A, Rb-Sr data of micas and U-Pb data for uraninites have been obtained. Table 3 contains similar data for additional pegmatites which have other uraninum- and thorium-containing minerals. Table 4 presents analytical data for granites from which both micas and zircons have been analyzed. The U, Th, and Pb analytical data are elsewhere [*Tilton* and others, 1957]. Table 5 gives the analytical data for micas from granites and pegmatites from which no U-Pb measurements have been obtained.

Ages—Using the decay constants of Table 1, ages may be calculated for each of the minerals of Tables 2–5. For K-A ages the results are calculated from

$$T = \frac{10^{10}}{5.30} \log_e \left(1 + 9.06 \frac{A^{40}}{K^{40}}\right) \text{ yr}$$

Each of the other four parent-daughter ages is given by

$$T = \frac{1}{\lambda} \log_e \left(1 + \frac{N_d}{N_p}\right)$$

where λ is the decay constant governing the system and N_d/N_p is the ratio of the number of daughter atoms to the number of parent atoms found in the mineral. The Pb^{207}-Pb^{206} age is obtained from curves plotted from the equation

$$\frac{N(Pb^{207})}{N(Pb^{206})} = \frac{1}{137.8} \frac{(e^{\lambda 235 T} - 1)}{(e^{\lambda 238 T} - 1)}$$

The data of Tables 2–5 are given in terms of ages in Tables 6–9. The uncertainty in the ages

TABLE 2 – *Analytical data for minerals from pegmatites having concordant U–Pb ages*

Location	Mineral	Radiogenic A^{40}	K^{40}	$\frac{\text{Radiogenic } A^{40}}{\text{Total } A^{40}}$	Rb^{87}	Radiogenic Sr^{87}	$\frac{\text{Radiogenic } Sr^{87}}{\text{Total } Sr^{87}}$	U	Th	Pb	Atom ratios		
											204/206	207/206	208/206
		ppm[a]	ppm[a]		ppm[a]	ppm[a]		pct	pct	pct			
Chestnut Flat Mine, Spruce Pine, N.C.	Uraninite[b]	...	...	...	...	...	...	65.4	...	3.67	$<4 \times 10^{-8}$	0.0547	0.111
	Uraninite[c]	...	...	...	...	...	...	74.8	...	3.98	4×10^{-8}	0.0553	0.0990
	Muscovite	0.232	10.89	0.97	270	1.43	0.82	...	...	...	...	...	...
					275	1.50	0.27						
	Potassium-feldspar	...	...	...	161	0.86	0.15	...	...	...	...	...	...
Fission Mine, Wilberforce, Ont.	Uraninite	...	...	...	...	...	...	59.7	11.8	10.1	$<1.5 \times 10^{-8}$	0.0749	0.0613
	Biotite	0.662	9.50	0.92	487	6.8	0.91	...	...	...	...	...	...
Cardiff Mine, Cardiff Twp., Ont.	Uraninite	...	...	...	...	...	...	66.0	9.68	10.6	$<2 \times 10^{-6}$	0.0724	0.0459
	Biotite	0.740	10.12	0.98	201	2.90	0.67	...	...	...	...	...	...
Bob Ingersoll Mine, Keystone, S.D.	Uraninite	...	...	...	...	...	...	64.55	2.93	17.01	3.0×10^{-8}	0.0990	0.0138
	Lepidolite	1.20	10.1	0.98	3140	73.2	0.99	...	...	...	...	...	...
	Muscovite	1.43	10.2	0.99	1157	28.2	0.98	...	...	...	...	...	...
Viking Lake Pegmatite, Sask.	Uraninite	...	...	...	...	...	...	55.3	5.46	17.3	4.5×10^{-6}	0.112	0.0282
	Biotite	0.864	4.98	0.96	326	9.0	0.95	...	...	...	...	...	...
Bikita Quarry, S. Rhodesia	Lepidolite	2.46	9.15	0.98	9370	356	0.99	...	...	...	...	...	...

[a] Parts per million by weight.

[b] Muscovite matrix.

[c] Quartz matrix.

TABLE 3 – *Analytical data for minerals from pegmatites with discordant U–Pb and Th–Pb ages*

Location	Mineral	Radiogenic A^{40}	K^{40}	$\frac{\text{Radiogenic } A^{40}}{\text{Total } A^{40}}$	Rb^{87}	Radiogenic Sr^{87}	$\frac{\text{Radiogenic } Sr^{87}}{\text{Total } Sr^{87}}$	U	Th	Pb^{206}	Atom ratios		
											204/206	207/206	208/206
		ppm[a]	ppm[a]		ppm[a]	ppm[a]		ppm[a]	ppm[a]	ppm[a]			
Brown Derby Mine, Gunnison County, Colo.	Microlite	...	...	...	...	...	...	62,100	...	8150	0.00063	0.0938	0.0255
	Columbite-Tantalite	...	...	...	...	...	...	1,280	...	337	0.00815	0.200	0.455
	Monazite	...	...	...	...	...	...	1,415	49,300	343	0.00099	0.0920	6.59
	Lepidolite[b]	1.02	9.4	0.98	5770	114	0.99	...	...	...	...	...	...
Harding Mine, Dixon, N.M.	Muscovite a	...	...	...	2180	40.4	0.99	...	...	...	...	...	...
	Muscovite b	...	...	...	1760	31.8	0.94	...	...	...	...	...	...
	Muscovite c	1.13	10.9	1.00	3930	75.7	0.99	...	...	...	...	...	...
	Muscovite d	1.10	10.5	1.00	2650	47.0	0.99	...	...	...	...	...	...
	Microlite, light	...	...	...	...	...	...	6,670	...	1003	0.00470	0.136	0.186
	Microlite, dark	...	...	...	...	...	...	76,600	...	10,150	0.00103	0.0926	0.0423

[a] Parts per million by weight.

[b] Average of seven micas for Rb-Sr and 5 micas for K-A.

because of analytical errors is less than five per cent unless indicated. Table 6 indicates the agreement of K-A and Rb-Sr ages with concordant U-Pb ages from pegmatites for which the latter ages are available. The ages for which this agreement has been measured are distributed over a time interval of 350 to 2700 m y.

Table 7 shows that for two pegmatites whose history is such that uranium- and thorium-containing minerals give ages which do not agree micas still give concordant K-A and Rb-Sr ages.

Table 8 demonstrates, first, that micas from granites generally give K-A and Rb-Sr ages which agree. Secondly, if the U-Pb ages of the zircon

TABLE 4 – *Analytical data for micas from granites for which zircon ages have been measured*

Location	Mineral	Radiogenic A^{40}	K^{40}	Radiogenic A^{40} / Total A^{40}	Rb^{87}	Radiogenic Sr^{87}	Radiogenic Sr^{87} / Total Sr^{87}
		ppm[a]	ppm[a]		ppm[a]	ppm[a]	
Bagdad, Ariz.	Muscovite	1.28	11.0	0.99	767	15.0	0.96
Quartz Creek, Colo	Biotite	1.02	9.51	0.69	334	6.15	0.97
Petrick Quarry, Llano, Texas	Biotite	0.370	4.48	0.94	115	1.77	0.68
Pikes Peak, Colo.	Biotite	0.496	6.67	0.95	234	3.49	0.76
Capetown, S. Africa	Biotite	0.292	8.67	0.96	310	2.60	0.94
Redstone, N.H.							
Green granite	Biotite	0.0822	7.72	0.95	414	1.10	0.61
Red granite	Biotite	0.0662	8.00	0.84	590	1.55	0.62
Wichita Mts., Okla.	Biotite	0.148	4.86	0.81	249	1.77	0.50

[a] Parts per million by weight.

TABLE 5 – *Analytical data for micas from pegmatites and granites for which no U-Pb ages are available*

Location	Mineral	Radiogenic A^{40}	K^{40}	Radiogenic A^{40} / Total A^{40}	Rb^{87}	Radiogenic Sr^{87}	Radiogenic Sr^{87} / Total Sr^{87}
		ppm[a]	ppm[a]		ppm[a]	ppm[a]	
Pegmatites							
Kubuta, Swaziland	Lepidolite	3.47	10.2	1.00	5050	209	0.99
Hearst, Ont.	Lepidolite	3.25	10.4	0.99	2600	94.4	0.99
Bonneville, Wyo.	Muscovite	2.43	9.65	0.99	5150	176	0.99
Silver Leaf Mine, Manitoba	Muscovite	2.36	10.1	0.97	6230	236	0.99
Varuträsk, Sweden	Lepidolite	1.72	10.5	0.97	5800	144	0.99
Bagdad, Ariz.	Lepidolite	1.21	10.2	0.99	3310	69.6	0.99
Wickenburg, Ariz.	Muscovite	0.968	10.9	0.99	4810	87.7	0.85
Pidlite Mine, Mora, N.M.	Lepidolite	1.07	10.0	0.94	3510	75.0	0.97
Bancroft, Ont.	Biotite	0.584	9.27	0.97	177	2.45	0.70
Jäkkalswater, S. Africa	Muscovite	0.711	10.3	0.95	2850	33.1	0.99
Karema Mine, Tanganyika Territory	Muscovite	0.773	10.8	0.96	121	1.8	0.19
Manano Mine, Belgian Congo	Lepidolite	0.509	8.2	0.97	3510	48.6	0.99
Muika, Belgian Congo	Lepidolite	0.576	8.4	0.96	3580	47.7	0.99
Pala, Calif.	Lepidolite	0.0560	10.5	0.86	4980	7.38	0.98
Granites							
Wind River Canyon, Wyo.	Biotite	0.350	3.04	0.95	116	3.17	0.77
Near Sherman, Wyo.	Biotite	0.954	8.09	0.98	294	5.83	0.88
Unaweep Canyon, Mesa Co., Colo.	Biotite	0.972	8.95	0.97	541	10.4	0.92
Albuquerque, N.M.	Biotite	0.904	8.27	0.99	240	4.56	0.66
Zoroaster Canyon, Grand Canyon, Ariz.	Biotite	0.957	8.44	0.97	136	2.57	0.86
Silver Plume, Colo.	Biotite	0.894	9.5	0.95	266	5.05	0.68
	Muscovite	0.781	7.9	0.92	127	2.42	0.22
Top of Pikes Peak, Colo.	Biotite	0.614	7.44	0.98	461	6.95	0.92

[a] Parts per million by weight.

are concordant, all four ages agree. Finally, if the U-Pb ages of the zircons disagree, the values for Pb^{207}-Pb^{206} ages are closest to the K-A and Rb-Sr ages of the associated micas.

Table 9 gives the K-A and Rb-Sr ages of micas from several pegmatites and granites for which no U-Pb ages have been accurately determined. The general agreement of these two ages is very satisfactory. The range in age for which this agreement exists is from 100 to 2600 m y.

Discussion—The K-A and Rb-Sr ages of Tables 6–9 together with the data of *Jeffery* [1956] are plotted in Figure 1. They are given in the form of a histogram of the ratio of the Rb-Sr age to the K-A

TABLE 6 – *Radioactive ages of minerals from pegmatites with concordant U-Pb ages*

Location	Mineral	Ages (m y)					
		K-A	Rb-Sr	U^{238}-Pb^{206}	U^{235}-Pb^{207}	Pb^{207}-Pb^{206}	Th^{232}-Pb^{208}
Chestnut Flat Mine, Spruce Pine, N. C.	Uraninite[a]	...	...	385	390	400 ± 50	...
	Uraninite[b]	...	...	370	375	420 ± 50	...
	Muscovite	335	375	...	...	...	...
	Potassium-feldspar	...	385	...	...	...	...
Fission Mine, Wilberforce, Ont.	Uraninite	...	...	1040	1060	1090	1010
	Biotite	920	1000	...	...	...	...
Cardiff Mine, Cardiff Twp., Ont.	Uraninite	...	...	1020	1020	1020	995
	Biotite	960	1030	...	...	...	...
Bob Ingersoll Mine, Keystone, S.D.	Uraninite	...	...	1580	1600	1630	1440
	Lepidolite	1380	1650	...	...	...	...
	Muscovite	1550	1730	...	...	...	...
Viking Lake pegmatite, Sask., Canada	Uraninite	...	...	1790	1830	1850	1600
	Biotite	1780	1970	...	...	...	...
Bikita Quarry, S. Rhodesia	Lepidolite	2310	2680	...	...	...	...
	Monazite[c]	...	...	2640	2670	2700	2640

[a] Muscovite matrix.
[b] Quartz matrix.
[c] Recalculated from *Holmes* [1954].

TABLE 7 – *Radioactive ages for minerals from pegmatites with discordant U-Pb ages*

Location	Mineral	Ages (m y)					
		K-A	Rb-Sr	U^{238}-Pb^{206}	U^{235}-Pb^{207}	Pb^{207}-Pb^{206}	Th^{232}-Pb^{208}
Brown Derby Mine, Gunnison Co., Colo.	Microlite	...	...	915	1055	1350	...
	Columbite-Tantalite	...	...	1520	1470	1390	...
	Monazite	...	...	1590	1420	1170	995
	Lepidolite[a]	1300	1410	...	...	...	...
Harding Mine, Dixon, N.M.	Muscovite a	...	1320	...	...	...	...
	Muscovite b	...	1290	...	...	...	...
	Muscovite c	1250	1350	...	...	...	...
	Muscovite d	1260	1260	...	...	...	...
	Microlite, light	...	...	970	960	940	...
	Microlite, dark	...	...	920	1000	1180	...

[a] Average of seven micas for Rb-Sr and five micas for K-A.

age of micas. The histogram includes all micas analyzed at the Carnegie Institution before February 1957. Where more than one mica from a rock has been analyzed the ratios are averaged and plotted as one square in the histogram unless the two ratios are markedly different. The histogram shows two particular characteristics of the ages. First, the K-A and Rb-Sr ages agree within ten per cent for over 60 pct of the rocks measured. Second, when the two ages disagree by more than ten per cent, the Rb-Sr age is nearly always greater than the K-A age. This is interpreted as an indication of argon leakage from the mica. Since argon may have leaked, the possibility remains that some of the Sr^{87} may also have been lost from the mica so that neither age can safely be considered to be absolute.

The first characteristic shown by the histogram

TABLE 8 – *Radioactive ages for minerals from granites*

Location	Mineral	Ages (m y)					
		K-A	Rb-Sr	U^{238}-Pb^{206}	U^{235}-Pb^{207}	Pb^{207}-Pb^{206}	Th^{232}-Pb^{208}
Bagdad, Ariz.	Muscovite	1360	1390	...	...	...	...
	Zircon	...	...	630	770	1210	270
Quartz Creek, Colo.	Biotite	1280	1310	...	...	...	...
	Zircon	...	...	925	1130	1540 ±140	530 ±110
Petrick Quarry, Llano, Texas	Biotite	1060	1100	...	...	...	...
	Zircon	...	...	950	990	1070	890
Pikes Peak, Colo.	Biotite	980	1020	...	...	...	...
	Zircon	...	...	625	710	980	313
Capetown, S. Africa	Biotite	505	600	...	...	...	...
	Zircon	...	...	330	355	530 ±40	238 ±30
Redstone, N.H.							
Green granite	Biotite	168	190	...	...	...	...
	Zircon	...	...	187	184	140 ±60	190
Red granite	Biotite	137	183	...	...	...	...
Wichita Mts., Okla.	Biotite	460	510	...	...	...	...
	Zircon[a]	...	...	520	527	550	506
	Zircon[b]	...	...	514	522	550	493

[a] Zircon has extensive radiation damage, contains 2060 ppm U, 8120 ppm Th.

[b] Zircon has little radiation damage, contains 414 ppm U, 1337 ppm Th.

demonstrates the general occurrence of the agreement of the K-A and Rb-Sr ages of micas from granitic rocks. Tables 7 and 8 demonstrate that the agreement of K-A and Rb-Sr ages is common even when the U-Pb ages of minerals from the same rock are discordant. This work indicates that the probability of obtaining concordant ages by K-A and Rb-Sr methods on mica is exceeded only by that of obtaining concordant U-Pb ages on pegmatitic uraninites. This is an empirical fact which has no obvious physical or chemical basis. It should be pointed out, that the decay of U and Th involves a far greater disturbance of the crystal structure than does the decay of either Rb or K. Sr^{87} and A^{40} originate with a maximum recoil energy of two and 24 electron volts, respectively, while the decay series of U^{238}, U^{235} and Th to lead involve the emission of six to eight alpha particles which produce nuclei with recoil energies on the order of 100,000 electron volts each. The fact that metamict zircon, the Wichita Mountain sample, for example, has given concordant isotopic ages indicates that radiation damage is not the sole cause of discordant ages, but it may play a role in promoting lead loss when it does occur. When the K-A and Rb-Sr ages of a mica disagree, both ages must be regarded with suspicion.

The preceding data indicate that micas give reliable ages for a majority of granitic rock samples. It is then reasonable to discuss a few conclusions of geological interest.

The measurements, including those of *Jeffery* [1956] and *Nicolaysen* [1954], demonstrate that rocks approximately 2600 m y old exist in North America, Africa, and Australia. Since these pegmatites intrude volcanic and sedimentary formations, rocks older than these pegmatites are known to exist. Mica probably offers the most attractive possibility for determining the ages of these more ancient rocks. The Varuträsk pegmatite should not be grouped with these oldest pegmatites as suggested by *Ahrens* [1955].

Another group of measurements of interest is that of the intrusive rocks of the Granville subprovince. From field relationships, *Satterly* and *Hewitt* [1955] have determined that in the sequence of intrusive rocks in the Bancroft region the Fission Mine belongs to the youngest group and the

TABLE 9 – *K-A and Rb-Sr ages of micas from granites and pegmatites*

Location	Mineral	Ages K-A	Ages Rb-Sr
		m y	m y
Pegmatite			
Kubuta, Swaziland	Lepidolite	2660	2920
Hearst, Ont.	Lepidolite	2540	2600
Bonneville, Wyo.	Muscovite	2250	2420
Silver Leaf Mine, Manitoba	Muscovite	2160	2640
Varuträsk, Sweden	Lepidolite	1720	1760
Bagdad, Ariz.	Lepidolite	1380	1500
Wickenburg, Ariz.	Muscovite	1120	1300
Pidlite Mine, Mora, N. M.	Lepidolite	1280	1490
Bancroft, Ont.	Biotite	850	990
Jakkalswater, S. Africa	Muscovite	920	960
Karema Mine, Tanganyika Territory	Muscovite	950	1100 ±100
Manano Mine, Belgian Congo	Lepidolite	840	975
Muika, Belgian Congo	Lepidolite	915	950
Pala, Calif.	Lepidolite	89	106
Granite			
Wind River Canyon, Wyo.	Biotite	1350	1940
Near Sherman, Wyo.	Biotite	1380	1410
Unaweep Canyon, Mesa Co., Colo.	Biotite	1300	1370
Albuquerque, N. M.	Biotite	1300	1340
Zoroaster Canyon, Grand Canyon, Ariz.	Biotite	1340	1350
Silver Plume, Colo.	Biotite	1230	1350
	Muscovite	1210	1360
Top of Pikes Peak, Colo.	Biotite	1060	1080

nepheline pegmatite belongs to the oldest. From the data presented above one can say either that the time interval between these extremes is too small to be measured or that the activity during which the younger pegmatites were emplaced altered the biotites from the nepheline rocks in such a way that all traces of their previous history were removed.

A third group of samples is of some interest because of their geographic and chronological proximity. These are the twelve granites and pegmatites in Arizona, New Mexico, Colorado, and Wyoming the value of whose ages is close to 1350 m y. The close agreement of these ages is believed to be an indication of some large scale process of granitic rock formation which occurred 1300 to 1400 m y ago, one which has not been eradicated by any subsequent geological event such as the Laramide orogeny. Before these measurements there was no basis for associating these rocks.

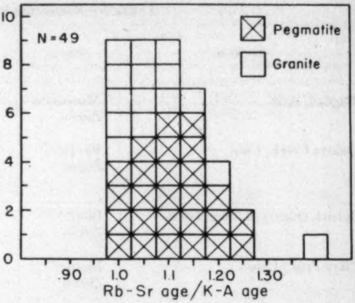

FIG. 1 – **Histogram of the ratio of the Rb-Sr age to the K-A age of micas from granites and pegmatites**

The two Pikes Peak samples had been thought from field evidence to be quite different in age [*Lovering* and *Goddard*, 1950]. From the K-A and Rb-Sr measurements it appears that, if a difference exists, it is less than the error of measurement. The Pikes Peak sample from the road cut between Manitou Springs and Pikes Peak Road also places an upper limit on the age of the Cambrian formation which unconformably overlies the granite. From these measurements it can be stated with considerable certainty that the Cambrian formation is younger than 1100 m y. While this may be considered an obvious fact, the statement is made to point out the difficulty of placing accurate ages on positions in the stratigraphic column. Intrusive rocks which cut one member of the column and are overlain unconformably by a closely adjacent younger member are rare. Thus any measurement, such as this one, which places an upper limit on the absolute age of a sedimentary rock of known geologic age is of considerable value until methods of measuring ages of minerals of sedimentary rocks are well established.

Several things may be said about the South African samples. First the diversity of the Cape granite ages may reflect the geologic history of the rock [*Nicolaysen*, 1954] in that the granite was depressed to great depth during the Devonian. The 'Cape System' rests unconformably on the Cape granite. The agreement of the Jakkalswater ages indicates that they are contemporaneous with the Steenkampskrall monazite analyzed by *Tilton* and *Nicolaysen* [1957]. The micas from the Belgian Congo and Tanganyika were thought to have a sequence which is not evident in the measured ages. The Tanganyika pegmatite was believed to be considerably older. Since these ages all agree within the errors of measurement, either the emplacement of all the pegmatites was simultaneous or else the event during which the Belgian Congo micas were formed removed all the evidence of the earlier history of the Tanganyika mica. The Bikita and Kubuta micas are from the group collected by Nicolaysen. The Bikita sample gives an age in good agreement with that found in Holmes for monazites from neighboring pegmatites. The Kubuta sample has the highest ratio, Sr^{87}/Rb^{87}, of any of those measured at this laboratory to this date. It also has the highest ratio A^{40}/K^{40}.

Conclusions—The results reported in the present study indicate that the rubidium-strontium and potassium-argon ages determined on single specimens of mica often agree within five to ten per cent. Since the two ages do not always agree, it should be emphasized that it is necessary to measure both ages on a mica in order to have full confidence in the result. When the two mica ages do agree, it is highly probable that they give the absolute age of the mica. Concordant uranium-lead ages given by zircon from granites and uraninite or monazite from pegmatites have been found to agree with K-A and Rb-Sr ages of mica. In such cases it is probable that the age closely represents the time of crystallization of the rock as a whole. Finally, the agreement of the two mica ages can often be preserved through processes which seriously alter the isotopic lead ages. Examples are the Brown Derby and Harding pegmatites and the Quartz Creek, Bagdad, Pikes Peak, and Capetown granites.

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APPENDIX

The following descriptions of the minerals for which ages are given in this paper are based on examinations of thin sections of the rocks, binocular microscopic determination of homogeneity, x-ray examination and identification, whichever is applicable. In cases where descriptions have previously been given, only new observations are listed. The samples are arranged in order of increasing age in each of three groups.

PEGMATITES CONTAINING URANINITES WITH ACCOMPANYING MICAS

Chestnut Flat Mine, Mitchell County, North Carolina—This mine is located about six miles north-northwest of Spruce Pine [*Olson*, 1944]. The uraninite specimen was collected from the margin of the core of the pegmatite as an aggregate of centimeter-sized pieces in a muscovite matrix. The mica was embrittled in the neighborhood of the uraninite, which was covered by a thin layer of orange-yellow alteration products. A clean sample was obtained by hand-picking the broken crystals. Fresh muscovite and microcline were obtained nearby where no uraninite occurred.

Fission Mine, Cardiff Township, Haliburton County, Ontario—Cubes of uraninite in a fluorite matrix were collected from Pit 4, 1.75 miles northwest of Wilberforce. *Satterly* and *Hewitt* [1955] list detailed information about the deposit. The uraninite required very little hand-picking for purification. A sample of clean biotite was collected from the same vein.

Cardiff Uranium Mine, Cardiff Township, Haliburton County, Ontario—This mine is located three miles south of the village of Wilberforce. The uraninite occurs as cubes in a matrix of fluorite, calcite, and apatite. The sample was collected from the north adit. Unchloritized biotite was collected from the same vein. A description of the property is given in some detail by Satterly and Hewitt.

Bob Ingersoll Mine, Keystone, South Dakota—This pegmatite is described by *Page* and others [1953]. The uraninite was collected from dumped material from Dike 1 as a single piece of pure mineral weighing about 250 g. A personal communication from Page states that the occurrence is not the one reported by him. This uraninite came from the outer margin of Dike 1, just outside the lepidolite body. Lepidolite and purple and white muscovite were also collected from the pegmatite.

Viking Lake pegmatite, Goldfields region, Saskatchewan—Specimens of uraninite (coarse powder), biotite, and other minerals were received from S. C. Robinson of the Geological Survey of Canada. These were collected one-half mile north of the north arm of Viking Lake from "an exceptional zoned pegmatite . . . in the Beaverlodge camp, has an outer envelope of quartz and euhedral microcline, an intermediate zone of highly sericitized sodium feldspar with some biotite and accessory magnetite and pyrochlore, and a core of brecciated but fresh microcline-albite-quartz-biotite rock which contains abundant pyrochlore, titanite and magnetite, and accessory uraninite, urano-thorite, cyrtolite, meta-allanite, and allanite." (S. C. Robinson, 1955, *Mineralogy and geochemistry of uranium in Canada*, preprint 284, Nuclear Engineering and Science Congress, publ. Amer. Inst. Chem. Eng.). X-ray examination of the biotite produced an unsatisfactory diffraction pattern indicating extensive chloritization.

Bikita Quarry, Bikita district, Southern Rhodesia—The isotopic analysis of a sample of monazite from the Ebonite Tantalum Claims has been reported by *Holmes* [1954]. The ages have been recalculated from the uranium and lead data given. Lepidolite from Bikita collected by L. O. Nicolaysen is sample N-45 of the intralaboratory series [*Aldrich* and others, 1956c].

GRANITES

Conway Granite, Redstone Quarry, Redstone, New Hampshire—The usual pink Conway granite and a green hastingsite phase were collected at the quarry at Redstone. The area and its rocks are described by *Billings* [1928, 1956]. The biotite from the pink granite occurred as ragged grains, partially chloritized, but a good sample was obtained by magnetic separation. The green rock provided good biotite. This phase also contains hornblende, apatite, magnetite and several rare minerals.

Cape Granite, Lower Cable Station Quarry, Capetown, South Africa—The biotite from this rock is partially chloritized [*Nicolaysen*, 1954].

Wichita Mountains, Oklahoma—The zircon is from a pegmatite on Quanah Mountain. *Tilton* and others [1957] give a description of the samples. The biotite was separated from a granite collected from a road cut on the west shore of Lake Altus Reservoir, 0.65 miles south of the Quartz Mountain State Park. This location was suggested by W. C. Hamilton of the U. S. Geological Survey and the sample was collected by E. E. Glick, B. R. Haley, and P. T. Stafford of the Survey.

Pikes Peak granite, near Manitou Springs, Colorado—Although collected from a road cut between Manitou Springs and Pikes Peak Road, this granite shows evidence of considerable alteration. Thin-section examination shows that the feldspar has been kaolinized and the mica extensively chloritized. This general characteristic is noted by *Lovering* and *Goddard* [1950].

Granite from the top of Pikes Peak, Colorado—A red, fine-grained rock collected from near the parking lot at the end of the toll-road at the top of the mountain yielded a sample of biotite which is partially chloritized.

Petrick Quarry, Llano, Texas—This granite is dark pink, somewhat porphyritic and coarse grained. The biotite is not chloritized. A description is given by *Barnes* and others [1947]. The location is north of the intersection of Texas Routes 29 and 261, 17 mi east of Llano.

Quartz Creek granite, Quartz Creek district, near Gunnison, Colorado—Described by *Aldrich* and others [1956a] after *Staatz* and *Trites* [1955]. The biotite is not chloritized but shows some signs of having been leached. It contains pleochroic halos and rod-like inclusions. Some secondary muscovite was noted.

Uncompahgre granite, Unaweep Canyon, Mesa County, Colorado—This is a slightly altered, white muscovite granite with accessory biotite and zircon.

Sandia granite, near Albuquerque, New Mexico—This white granite is exposed on the lower part of the Sandia Escarpment north east of Albuquerque. It is composed of sericitized plagioclase, biotite, apatite, rather large grains of sphene, and a little chlorite and magnetite.

Zoroaster granite (gneiss?) at the mouth just west of Zoroaster Creek Grand Canyon, Arizona—This rock occurs as "a rather massive, medium-grained, muscovite-biotite-granite" (*Carnegie Institution Yearbook 35*, 1935–1936, p. 330). It is overlain unconformably by sandstones and basal breccia of the Tonto Platform. In thin section the rock has a crushed appearance, the biotite being curved and rusty. The muscovite is in good condition. Zoisite is present in minor amounts.

Lawler Peak granite, ¾ mile northeast of Lawler Peak, Bagdad, Arizona—The area is described by *Anderson* and others [1955]. Thin-section examination showed the presence of secondary muscovite formed from alteration of the plagioclase. The coarser primary muscovite was readily separated for analysis.

Granite, Sherman Mt. Quadrangle, Wyoming—Collected from road cut on U. S. Route 30, 18 mi east of Laramie. Petrographic examination of a thin-section showed that the biotite, containing inclusions of sphene or zircon, and pleochroic halos, was considerably chloritized, however, a good sample of biotite was separated for analysis.

Silver Plume granite, Silver Plume, Colorado—This granite was collected from a quarry half a mile west of Silver Plume. *Lovering* and *Godard* [1950] consider this granite to be representative of the Precambrian granites younger than the Pikes Peak granite. The material collected was a fine grained, gray, massive rock which contained biotite, moderately chloritized, muscovite, fluorite, and sphene.

Wind River granite, Wind River Canyon near Shoshone, Wyoming—This rock has been described by *Gwynne* [1938]. It was collected as the closest granite to the Bonneville pegmatites [*McLaughlin*, 1940]. Thin-section examination showed extensive chloritization of the biotite, which occurs in veins mixed with muscovite. The presence of hydrothermal muscovite was noted.

OTHER PEGMATITES

Pala, California—Lepidolite, interlaboratory series no. A 107.

Goulding-Keene Quarry, Bancroft, Ontario—Pegmatite 6.8 mi east of Bancroft, on the road to Herman on the west side of the York River. Nepheline-albite pegmatite with calcite, biotite, apatite and zircon. X-ray of biotite showed no chlorite.

Jakkalswater, Cape Province, South Africa—Muscovite; for description see *Nicolaysen* [1954].

Muika, Belgian Congo—Lepidolite; for description see *Nicolaysen* [1954].

Manano, Belgian Congo—Lepidolite, from Belgian Congo Museum. Pegmatites described by J. Thoreau in *Commémoration du 50e Anniversaire du Comité Spécial du Katanga*, Comtes Rendus du Congrès Scientifique, Elizabethville, 1950, vol. 2, pp. 333–368. Sample provided by L. Cahen.

Karema, Tanganyika Territory—Muscovite, from Ubendian belt. Sample provided by L. Cahen.

Harding Mine, Dixon, New Mexico—Lepidolite, purple and white muscovite and yellow and brown microlite were obtained from the pegmatite under the guidance of the owner, Arthur *Montgomery* [1953] who has described the geology of the area. The identification of the micas and the light colored microlite was verified by x-ray. The dark brown microlite (hatchettolite?) showed no structure, indicating complete destruction of the lattice by radioactivity. The purple micas have been discussed by *Schaller* and *Henderson* [1926].

Wickenberg, Arizona—Purple muscovite. The sample was collected from a pegmatite on the fork of San Domingo Wash near Riley's Place.

Brown Derby Mine, Ohio City, Gunnison County, Colorado—Lepidolite and muscovite. See *Aldrich* and others [1956a].

Pidlite Mine, Mora County, New Mexico—Lepidolite was collected with Arthur Montgomery from this pegmatite which has been described by *Jahns* [1953].

Bagdad, Arizona—Lepidolite was collected from a pegmatite in the Lawler Peak granite under the guidance of C. A. Anderson within ¼ mile of the granite location.

Bob Ingersoll Mine, Keystone, South Dakota—Purple muscovite, interlaboratory series no. A 106.

Varuträsk, Sweden—Lepidolite, interlaboratory series no. A 110.

Bridger Mountains, near Bonneville, Wyoming—Purple muscovite was collected at Locality 7 or 11 described by *McLaughlin* [1940].

Silverleaf Mine, S. E. Manitoba—Purple muscovite, interlaboratory series no. A 109.

Hearst, Ontario—Lepidolite obtained from S. A. Ferguson, Ontario Department of Mines, Timmins, Ontario. Collected from a pegmatite in pink granite occurring on Concession 4, Lot 7, Lowther Township.

Kubuta, Swaziland—Lepidolite collected and described by *Nicolaysen* [1954].

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Areas of Tectonic Activity in the United States As Indicated by Earthquake Epicenters

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Abstract—A study based on earthquake occurrences in the United States shows several zones of continuing seismic activity. Over the past 30 years there is a suggestion of systematic variations in seismic activity following what appears to be a three-year cycle which is superimposed on a longer period. Areas of activity can not be related to either geologic age or type of structure. In California transcurrent movement on known faults is associated with seismic activity. In the other western states activity is associated with the boundaries of areas of epeirogenic uplift and subsidence and appears to involve predominantly vertical crustal displacement. In the Midcontinent area activity for the most part is associated with positive crystalline rock tectonic elements and their borders. In the Appalachian area activity is associated with the zones of overthrusts and shear. A conspicuous zone of earthquakes paralleling the Appalachians from Missouri to the St. Lawrence River valley while not related to known geologic controls does follow a zone of better-than-normal seismic transmissibility. The depth of focus varies from area to area and appears to be related directly to crustal thickness and possibly also changes in crustal rigidity with depth. No direct relation is noted between areas of isostatic unbalance and seismic activity or variations in degree of seismic activity with changes in crustal thickness. For the most part, it appears local stress conditions are dominant in causing earthquakes.

Introduction—That the geographic distribution of earthquakes has tectonic and geologic significance has been recognized for many years. *Gutenberg* and *Richter* [1940] have pointed out that the principal seismic regions of the earth are distributed along the borders of great lines of folding marked by high chains of mountains and the great oceanic trenches. In general it has been observed that the intensity of seismic activity appears to be related to the geologic age of the tectonic elements involved; the older they are the less intense the seismic activity. However, the role of rejuvenation in causing earthquakes is indicated by the many earthquakes which occur in elevated former peneplains now forming plateaus. Regional stresses are also indicated in the old stable shield areas of low elevation by the occurrence of major earthquakes in areas such as the Mississippi River valley. Compressive and tensional forces, horizontal shear, and rotational forces all are observed to have been active in forming geologic tectonic units, and earthquakes are evidence of these forces in action. In some areas tectonic movement in association with individual earthquakes can be seen, in other areas there is no observable crustal displacement.

Over 90 pct of all earthquakes occur within the surficial crustal layer whose base is defined by the Mohorovicic discontinuity. The spatial distribution of focal points of origin of earthquakes and the frequency of earthquakes at different levels has significance as to tensional and compressional forces in the crust and outer mantle rocks. *Benioff* [1955] has shown that deep-focus earthquakes are systematic in location and define shear planes suggesting local underthrusting of the continents by the adjacent oceanic block. Deep-focus earthquakes are rare in the United States although they do occur in Mexico.

Various investigators have described geological associations noted with individual earthquakes and the tectonic movement involved. *Wood* [1947], *Gutenberg* [1943], and *Hill* and *Dibblee* [1953] have described the relation of earthquakes to transcurrent fault movement in Southern California. *Jones* [1938] has described the increase in depth of focus of earthquakes as the vent of Mauna Loa Volcano is approached on the island of Hawaii. *Barksdale* and *Combs* [1946] have described the association of earthquakes with the Puget Sound depression. *Taber* [1916], *Crickmay* and *Mitchell* [1935], and *MacCarthy* [1958] have commented upon the occurrence of earthquakes in association with the thrust fault area of the older Appalachians and the shear zones of the Atlantic Piedmont. *Collins* [1937] and *Billings* [1942] have noted a correlation of earthquakes with areas of granite intrusion in New England. *Leet* [1942] has attributed earthquakes and their alignment in the northeastern states to domal uplift of the Canadian shield as a result of crustal unloading occasioned by the melting of the Pleistocene ice cap. *Pardee* [1927] has described the association of earthquakes with the Bighorn Mountain uplift in Wyoming.

Jones [1915] and *Gianella* and *Callaghan* [1934] as well as others have described structural movement and fracture patterns developed as a consequence of earthquake activity in the Basin and Range area of Utah and Nevada.

Callaghan and *Gianella* [1935], *Larson* [1957], *Leet* [1936], *Pardee* [1950], *Rockwood* [1872–1886], *Slemmons* [1957], and *Whittier* [1957] have collected valuable information regarding various earthquakes and associated tectonic features. The results of the above works have been incorporated into the regional analyses of tectonic activity.

The present study differs from these earlier ones in that the writer has undertaken to examine the United States as a whole with attention to: (1) areas experiencing tectonic movement as evinced by earthquakes, (2) possible changes in earthquake activity and location with time, (3) the geologic associations in areas now undergoing structural dislocation as indicated by earthquakes, and (4) variations in depth of origin of earthquakes, especially as related to geologic provinces, crustal structure and isostatic compensation. This study was started in 1937 under the auspices of the Special Committee for the Geophysical and Geological Study of the Continents of the Union and with the cooperation of the late N. H. Heck of the U. S. Coast and Geodetic Survey and late H. F. Reid of Johns Hopkins University. While there have been no previous published reports on the study, a map showing the location of all known earthquakes in the United States was exhibited at the 1939 meeting of the International Union of Geodesy and Geophysics in Washington and revised maps have appeared from time to time in the published report of the Special Committee.

In preparing the present paper three sources of data have been used, (1) the yearly reports, files and library of the *U. S. Coast and Geodetic Survey* [1924–27; 1928–55], also *Heck* [1938], *Wood* and *Heck* [1941], (2) the unpublished card index of earthquakes based on newspaper reports compiled by the late Harry Fielding Reid who prior to his death made this material available to the writer, and (3) current literature. The assistance and cooperation of the U. S. Coast and Geodetic Survey Seismological Section over the past twenty years in keeping the study up to date is most gratefully acknowledged.

Areas of tectonic activity—Figure 1 shows the location of earthquakes in the United States as reported by the U. S. Coast and Geodetic Survey through 1957. Newspaper reports not substantiated by the records of the Coast and Geodetic Survey have not been used in order to keep the data as authentic as possible. In the West Coast

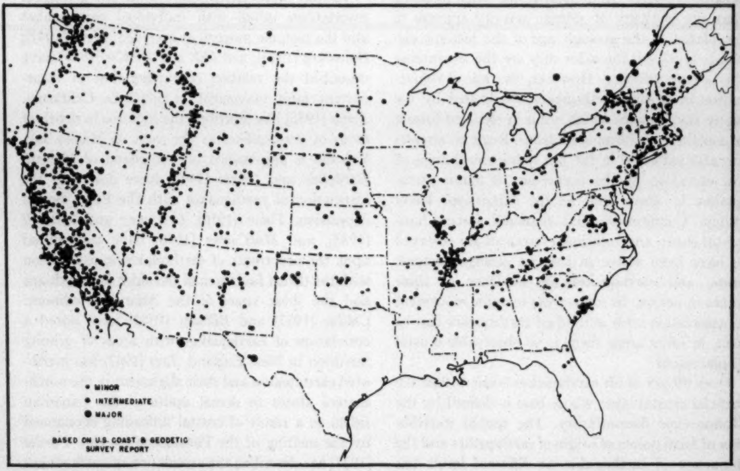
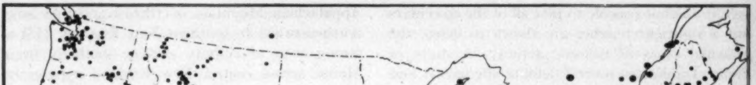


Fig. 1 – Earthquakes in the United States through 1957

area it was not feasible to plot all of the epicenters but a sufficient number are shown to define the principal areas of tectonic activity. A study of Figure 1 indicates several definite alignments and areas of marked seismic activity, the principal ones being: (1) the Puget Sound area of Washington, a known tectonic depression, (2) the California Coastal area south of Cape Mendochino, a zone of strike slip fault movement involving several faults of which the best known are the San Andreas Fault and Garlock Fault, (3) the eastern boundary of the Sierra Nevada batholith and adjacent block faulted area of the Great Basin, (4) the area around Carson City, Nevada, an area of block faulting involving both horsts and grabens as well as the buried northward extension of the Sierra Nevada batholith, (5) an alignment striking southeasterly from Puget Sound across Idaho to northern Utah which conforms in position and strike with structural axes crossing the Columbia River plateau, (6) an alignment striking southwesterly from northeast Utah to south of Carson City, Nevada, following topographic trends of the Basin and Range structure, (7) an alignment following the Rocky Mountain front zone of overthrusts in Montana which switches across to the Wasatch Mountain front in Utah to continue southward through Arizona following known faults, (8) a short alignment striking northeasterly in central Montana paralleling the Little Belt Uplift-Bowdoin Dome structural axis, (9) an alignment striking north-south in New Mexico associated with the fault boundaries of the Rio Grande basin, (10) a broad area of rather random distributed epicenters covering Wyoming, Colorado, South Dakota, Nebraska, and Kansas associated in part with known features such as the front of the southern Rocky Mountains and in part with buried basement rock structures, (11) an apparent east-southeast alignment running from the Texas Panhandle into Arkansas associated in part with the Amarillo-Wichita Uplift and in part with the Ouachita Mountain thrust zone, (12) a north-south alignment from the Tennessee-Mississippi line extending through St. Louis, Mo., in part related to known faulting and in part to unknown geologic controls, (13) an alignment striking northeasterly from the Missouri-Kentucky area across southern Indiana and Ohio, into the St. Lawrence River valley, for the most part not related to any known geologic controls except in the St. Lawrence River valley, (14) an alignment from central Alabama following the Appalachian Mountain overthrust and fold zone northeastward to southern New England, (15) a strong zone of activity striking southerly from Maine across central New England apparently related in part to intrusive granitic bodies, (16) a localized zone of activity in northern New York following the northern boundary of the Adirondack massif, (17) an alignment following the coast from the head of Chesapeake Bay to Cape Cod which parallels the structural trends in the adjacent crystalline rocks, (18) a local zone in central Virginia for the most part along an axis transverse to the local structural trends of the observable rocks, (19) a local zone in South Carolina having a similar relation to structure as observed in Virginia, and (20) a local alignment in central New England following the Connecticut River valley. There are other local zones of slight activity as in northern Florida over the Peninsula Arch, in Washington, Oregon, and California in association with the Cascade volcanic chain, in northern Illinois and southern Michigan where there is no known geologic control of the apparent alignment, and in the Alabama-Georgia-South Carolina Piedmont in association with the Piedmont fault zones.

Of equal interest are the areas which do not appear to have had earthquake activity during historic time. These include much of Oregon, eastern Nevada, southern Arizona, eastern Montana, North Dakota, Minnesota, Wisconsin, Iowa, most of Missouri, Texas, Louisiana, Kentucky, West Virginia, western Pennsylvania, southern Georgia, Alabama, Florida, and eastern North Carolina. The lack of earthquake activity in these areas cannot be related to lack of structural deformation and faulting, and it would appear therefore that local forces are more responsible for earthquakes than continent-wide regional forces. An alternate interpretation is that there is earthquake activity in these areas but of too low an intensity to be recorded instrumentally and that they are not being orally reported because of lack of population or failure of the local populace to recognize them as earthquakes. The writer, however, does not find a correlation between Figure 1 and the population density of the country and finds it difficult to believe Figure 1 represents variations in the intellectual level of the nation.

Variation in earthquake activity with time—In order to study the epicenter pattern in terms of continuity of activity, two maps are presented. Figure 2 shows epicenter locations for earthquakes prior to 1938 and Figure 3 shows epicenter posi-


• MINOR
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● MAJOR
BASED ON U.S. COAST & GEODETIC SURVEY REPORT

FIG. 2 – Earthquakes in the United States prior to 1938

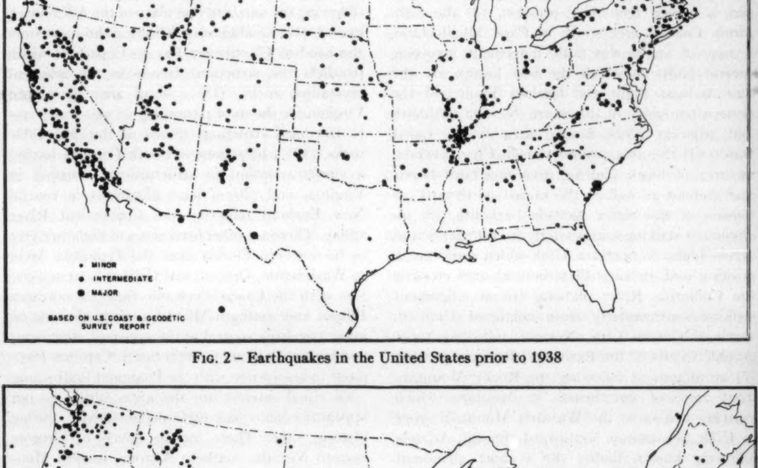
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FIG. 3 – Earthquakes in the United States, 1937–1957

tions for earthquakes since 1937. This division in time was purposely chosen in order to get an approximate even division in number of reported earthquakes. Since 1924, when the U. S. Coast and Geodetic Survey took over the responsibilities of keeping national archives on earthquakes, the number of seismological observations has markedly increased, the population has swelled, higher education is more universal, the news reporting services have greatly expanded and many previously uninhabited areas now have urban populations. As a consequence, very few earthquakes are now not reported or recorded. Prior to 1924, when the *U. S. Weather Bureau* [through 1923] kept the seismological record, the observatories were few, newspaper wire services did not have complete coverage, much of the country was essentially uninhabited and seldom visited because of poor roads, the educational level of the people and their interest in science was lower than now, and many earthquakes were never reported even when large enough to be noticeable by the local inhabitants. Prior to 1850 the situation was much worse and only major earthquakes constitute the record prior to that time.

While a 20-yr period is a rather short one in which to try and establish any significant trends, it does appear that there have been some real changes in that period. At first glance the two maps appear to be very similar, but there are points of difference. One of these is the cessation of activity indicated during the past 20 yr in the southern Idaho, northeastern Nevada, and northwestern Utah area. This area, in Figure 2, shows a well defined alignment of earthquake epicenters which cuts across the Snake River downwarp from the southern end of the Idaho batholith. Very little activity is indicated in this area in Figure 3. Another area of change is the alignment of epicenters striking to the northeast in central Montana shown in Figure 2. This alignment parallels the Little Belt Uplift-Bowdoin Dome axis. Since 1937 there appears to have been no seismic activity on this alignment. While activity in the other Rocky Mountain front states appears to have been maintained during the past 20 yr at about the same level as before, the pattern of disturbance has changed considerably. For example, Figure 2 shows a marked northeast trending alignment as a conspicuous feature in Wyoming. In Figure 3 the epicenters in the same area form two parallel alignments where only a single one was shown before. This trend is that of the main structural elements in the area, large horsts and grabens comprising the middle Rocky Mountains. The pattern and increase in activity over the last 20 yr suggests renewed rejuvenation in this area. This also is suggested by the large number of earthquakes in Montana along the Rocky Mountain front starting in 1935. In New Mexico there is a definite north-south alignment indicated for two parallel earthquake belts shown in Figure 2. One occurs in association with the Rio Grande basin in New Mexico and the other is associated with the front ranges of the southern Rocky Mountains. In Figure 3 a more disperse pattern of epicenters is shown for this area with a single southwest-northeasterly trend cutting across the state. While this trend can also be traced in the data of Figure 2, it is not nearly so pronounced. The north-south earthquake alignments follow the structural alignment of the tectonic units comprising the southern Rocky Mountains; the southwest-northeasterly trend is a cross-cutting one. In Arizona, where marked activity is shown in Figure 2 along the boundary of the Colorado Plateau and the Great Basin, only minor activity is indicated over the past 20 years. Another area of marked change in activity is the South Dakota, Nebraska, Kansas area. In Figure 2 considerable activity is indicated prior to 1938 along two parallel southwest-northeasterly trending axes and along a cross-cutting northwest-southeasterly trend. Since 1937 there has been only minor activity in this area. Similarly, a significant decrease in earthquake activity is shown in the northern Illinois, central Alabama, central New York, and northern Florida areas during the past 20 yr.

Summarizing the above it would appear that while the areas of most numerous earthquakes, as California, the Missouri-Illinois border area, New England, South Carolina, and Virginia, show continuous activity, there has been a notable decrease in activity in the northern Midcontinent area, the lower southeastern states, the Idaho, Utah, Nevada border area, and in Arizona. Only in the middle Rocky Mountain region of Wyoming does there appear to have been a significant increase in activity during the last 20 yr period. The changes in epicenter alignment without significant changes in earthquake activity, as in New Mexico and the Midcontinent area, suggest a change in stress direction. All of these observations tend to support the idea of localized stress and strain relationships determining centers of earthquake activity rather than regional, continent-wide stress conditions.

If the data for the past 34 yr, representing the period during which the U. S. Coast and Geodetic Survey has been keeping a systematic record of earthquake activity in the United States, is considered on a yearly basis in terms of which of the seismic areas outlined showed activity, a somewhat different picture is obtained. This material is summarized in Table 1, which indicates not only whether there was activity in each area but whether there were any major earthquakes (VII or greater on the Modified Mercalli scale). These

TABLE 1 – *Seismic areas having activity, 1924–1954*

Year	Puget Sount	California Coast	East side, Sierra Nevada	West side, Idaho Batholith	South side, Coast Range Batholith	Rocky Mt. front (Mont.)	Great Basin - Colorado Plateau Boundary	Central Colorado Plateau	So. Rocky Mt. front	Plains area	Tenn. - Mo. - Ill. - Ind. - Ky. junction	St. Lawrence River - Ohio alignment	Appalachian Mt. thrust zone	South Carolina	Central Virginia	Northern New England	Central New England	Northeast Coastal Alignment
1924		x				x	x			x	x	x	x	x				x
1925	x	X				X	x		x	X	X	X			x	x	x	x
1926		X				x	x		x		x		x			x		
1927	x	X	X	x	x	x	x			x	X	x	x	x	x	x	x	X
1928	x	x	X	x		X	x	x		x	x	X	X	x	x	X	x	x
1929		x	x			x				X	x	X		x	x	x	x	
1930	x	X	X	x	x	x	x	x	x		x	x	x	x	x	x	x	x
1931	x	X	X	x	x	x	x	x	x	x	x	X	x		x	x	x	x
1932	x	x	X	x	x	x	x					x		x	x	x		
1933	x	X	X	x	x	x	X			x	x	x		x	x	x		x
1934	x	X	X		x	x	X	x		X	x	x		x	x	x	x	
1935	x	X	X	x	x	x	X	X		X	x		x	x	x	x		x
1936	x	X	X	X		X	x	x	x	X	x	x	x	x	x	x	x	
1937	x	X	x	x		x	x	x			x	X	x	x	x	x		x
1938	x	X	X	x		x	x	X		x	x	x	x	x			x	x
1939	X	X	X		x	x	x	x	x	x	x	x	x					x
1940	x	X	X		x	X	x	x			X	x	x	x		x	X	x
1941	X	X	X	x	X	x		x		x	x	x	x			x		x
1942	x	X	X	x	x	x	X	x		x	x			x	x			x
1943	X	X	X	x	x	x	X			X		x		x		x	x	X
1944	X	X	X	X	x	x	x	X			X	X		x		x	x	
1945	X	X	x	X	x	X	X			x	x	x	x	x	x		x	
1946	X	x	X		x	x	x	x		x	x		x	x	x	x		
1947	x	X	X	X	x	X	x	X			x		x	x				x
1948	x	X	X		x	X				X					x	x		x
1949	x	X	X	x		x	X		X	x	x		x	x	x	x		x
1950	X	X	X			X	X						x		x			x
1951	x	X	X							X	x	x		x	x		x	x
1952	x	X	x			X			x	X	x	x	x	x	x			
1953		X	X			X	x			X	X	x	x		x	x		x
1954	x	x	X	x	x	x	x	x			x	x	X			x	x	x

x minor activity
X earthquakes force VII

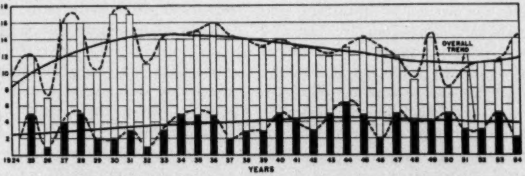


FIG. 4 – Activity in principal seismic areas in the United States as a function of time; solid bar, number of areas with major earthquakes; total bar, number of active areas

data are also presented graphically in Figure 4. The presentation used was chosen rather than one of yearly energy release since the latter would be so heavily biased by the large number of earthquakes in the California-Nevada region that variations over the rest of the country would be completely masked.

Starting with data for 1924, only nine of the 18 areas experienced earthquakes that year, and in none of them were there any earthquakes having an intensity as great as VII. The next year twelve areas were involved and in five of these there were earthquakes of intensity VII or greater. From the overall plot it is seen that there is a suggestion of a short period (3- to 5-yr) cyclic variation in activity and that this is superimposed on a much longer term period which appeared to reach a peak during the period 1931–1936, during which time an average of 14 of the 18 areas showed activity. After that time there was an overall decrease in activity reaching a minimum in the period 1951–1953 when an average of only ten of the areas showed activity. In terms of the occurrence of earthquakes having an intensity of VII or more, the variations also appear to follow the same pattern with a 3- to 5-yr cycle superimposed upon a longer term variation. A gradual increase in number of areas affected increased from about two in 1924 to four in 1944, with a decrease since. For the most part the variations in number of areas having activity and large earthquakes parallel each other from 1924 through 1941. From 1948 on, though, the two curves appear to be out of phase. The significance of these variations is not obvious, but it appears there are at least two superimposed sets of widespread regional forces in addition to those of local origin influencing the occurrence of earthquakes in the United States.

Relation to geology—While a general correlation with geologic features has been given in identifying the principal areas of earthquake activity, it is of interest to examine the relations in more detail. Figure 5 shows a plot of all earthquakes, including those from the unpublished compilation by Reid based on newspaper reports, superimposed on a map showing the main tectonic elements of the United States. This plot suggests that the tectonic forces affecting each area of activity results in earthquakes involving more than a single tectonic element in each area. The resolution of the forces present is difficult to assess since surface structural features may be either of an earlier origin or only superficial and not reflect correctly dominant structure and movement at depth where an earthquake originates. For example, surface graben, an extensional feature, may develop equally well as a result of horizontal tensional forces or as a result of vertical uplift as is seen in connection with salt dome structures. Also, in some areas there may be a combination of forces present involving both horizontal shear and uplift. To deduce correctly the tectonic significance of earthquakes associated with surface tectonic units therefore require a knowledge of many factors, most of which are usually not known. Even in seismic areas such as Southern California where the geologic relations appear to be well established [*Wood*, 1947; *Gutenberg and Richter*, 1953; *Hill and Dibblee*, 1953] and the dominant crustal movement is known to be strike slip motion along the coast with the west side of California moving northward relative to the east side, and with complementary motion at the southern terminus of the Sierra Nevada batholith such that the north side is moving westward relative to the south side, competent investigators disagree as to the stress pattern present. *Gutenberg and Richter* [1953] conclude "much of the faulting can be described in terms of a north-south compression." *Menard* [1955] on the other hand concludes the maximum compression is oriented about S 40° W.

Without going into the evidence as to which of the above two interpretations is probably correct, the present writer would like to point out that this region, while undoubtedly undergoing shear movement as a result of compression, is also subject to the vertical forces that seem to characterize all of the western states. For example, fault scarps were developed in Owens Valley on the east side of the Sierra Nevada block during the earthquake of 1872 indicating uplift of the Sierra block. Also, a glance at Figure 5 shows the occurrence of many earthquakes within the Sierra Nevada block itself suggesting rejuvenation of this tectonic arc.

A similar situation is indicated along the eastern boundary of the Great Basin where there are newly developed scarps with displacements as much as 40 feet along the Wasatch Front [*Fenneman* 1931]. *Eardley* [1951] has called attention to the alignment of earthquakes from the eastern Rocky Mountain front in Montana southward through Utah into Arizona following the zone of great trenches bordering the Rocky Mountain Colorado plateau block. Since the trench areas are bounded by high-angle gravity faults, it seems likely that the trenches are related to a common regional set of forces. From the geologic associations it appears that the boundary faults of the trenches are related to vertical uplift of the adjacent positive tectonic elements. Sedimentary loading from the adjacent highland presumably, with time, develops tilting of the trench block. This is suggested by the history of progressive although intermittent movement on the Hurricane Fault in Utah, which is one of the currently active trench boundary faults as indicated by earthquakes. According to *Gardner* [1941] the Hurricane Fault, which is about 170 mi in length, was formed in late Miocene or Pliocene time with about 8000 ft downward displacement of the western (Basin) block. Following a long period of quiet, during which all topographic

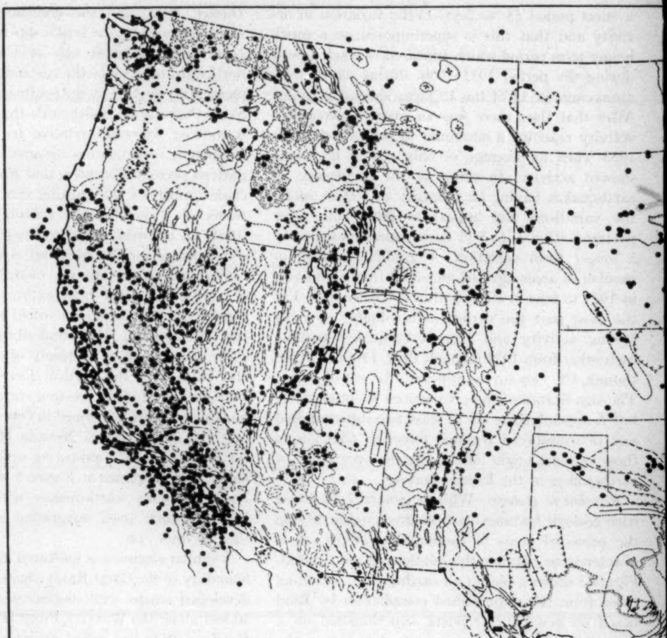
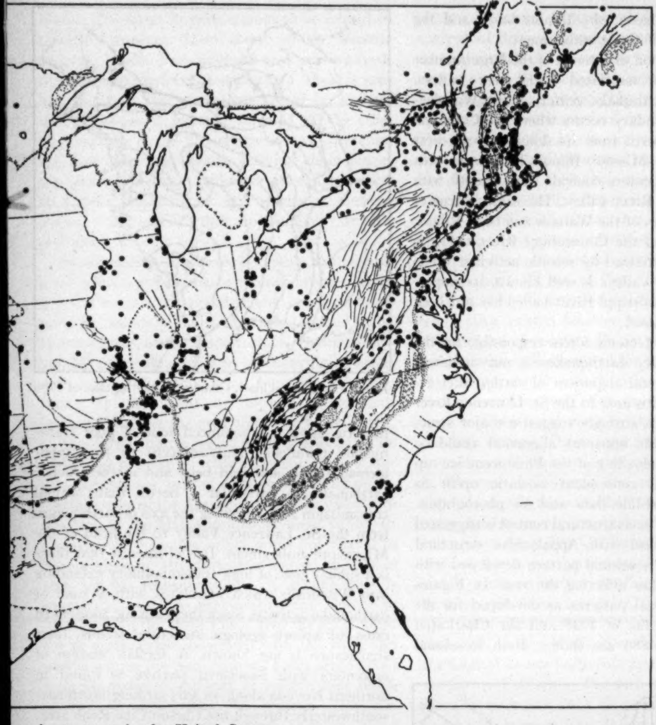


FIG. 5 – Relation of earthquake epice

evidence of differential movement was erased, the area was covered by Quaternary basalts. Since that time there has been renewed movement with tilting and about 1000 ft relative downward displacement of the Basin block. It would be of interest to make a series of precise gravity measurements as well as triangulation and precise leveling measurements in this area over a period of time to determine which or if both blocks are undergoing movement.

Using the past recent geologic history of the western states as deduced from physiographic evidence, there has been considerable epeirogenic uplift of the whole area which from the earthquake epicenter pattern appears to be continuing. This regional movement would not be expected to develop new fractures so much as to result in considerable adjustment of crustal blocks along old fracture lines developed at different times in the geologic past under varying stress conditions. Any attempt at regional stress analysis from the epicenter pattern is therefore bound to invoke a lot of hypothetical conditions of questionable validity. The fact that most of the earthquake activity in the western states outside of California is confined to the boundary area of the Great Basin and adjacent Sierra Nevada block on the west and the Rocky Mountain-Colorado Plateau block on the east, with some activity on the east flank of the Rocky Mountain block suggests there is unit uplift of the positive blocks and possible subsidence of the intervening Basin and Range



ctonic structure in the United States

block. Local uplift is also suggested along the western boundary of the Idaho batholith and the southern boundary of the Loon Lake, Colvin, and other batholiths in the state of Washington with possible subsidence of the adjacent Columbia River basalt area. This area undoubtedly underwent considerable subsidence with the emplacement of the basalts but it is not likely that subsidence of this block is continuing now that eruption has essentially ceased, particularly in view of local uplift of such features as the Blue Mountains in the plateau area.

In the Great Plains earthquake activity is confined principally to positive tectonic elements and their boundaries, such as the Black Hills, Chadron arch, Sioux uplift, Amarillo-Wichita uplift, Abilene arch, and Sierra Grande uplift. In the middle Rocky Mountains it also is noted that the earthquakes occur in connection with the boundary of positive elements such as the Bighorn uplift, Owl Creek uplift, Wind River uplift, Sweetwater arch, and Laramie uplift. Likewise, in the central Rocky Mountains the earthquakes are associated principally with the uplifts as the Rock Spring uplift, White River uplift and Uncompahgree uplift. The intermontane Rio Grande valley in central New Mexico is the only structural basin in the Rocky Mountain block that appears to have an extensive series of earthquakes associated with it rather than with the adjoining positive blocks. Other structural basins showing marked earthquake activity are the Puget Sound depression, the Anadarko basin, the Illinois basin and the head of the Gulf Coast embayment.

One observation of interest is the large number of earthquakes associated with river valleys. The marked earthquake center on the Washington-Oregon boundary occurs where the Columbia River swings north from its dominant east-west path. In the Missouri-Illinois-Tennessee area earthquake epicenters coincide very closely with the Mississippi River valley. The same is true of the lower reaches of the Wabash and Ohio Rivers. In New England the Connecticut River valley is similarly characterized by seismic activity. While fault control of valleys is well known, its importance in the Mississippi River valley has not been generally recognized.

Although the tectonic forces responsible for the Mississippi Valley earthquakes is not definitely known, the general alignment of earthquakes extending out of this area to the St. Lawrence River valley in Canada strongly suggest a major structural break. This apparent alignment could be related to the unloading of the Pleistocene ice cap in Canada and consequent isostatic uplift as evinced by level-line data and air photographs. That there may be a structural control is suggested by the parallelism with Appalachian structural trends and the isoseismal pattern developed with major earthquakes affecting the area. In Figures 6 and 7 isoseismal patterns as developed for the Quebec earthquake of 1925 and the Charleston earthquake of 1886 are shown. Both isoseismal patterns show a pronounced zone of poor transmission paralleling and adjacent to the Appalachian thrust and fold belt, and in the Quebec earthquake in particular a better than normal transmission zone following the axis of earthquakes from the St. Lawrence Valley to the head of the Mississippi embayment. It is of interest that there is a similar zone of high transmissibility extending into Wisconsin which correlates with a zone of earthquake activity. Since these seismic zones both cross-cut known geologic structural trends, their significance is not known. A similar relation of epicenters with isoseismal pattern is found in northern Nevada along an axis striking northeast-southwesterly through the Carson City-Reno area.

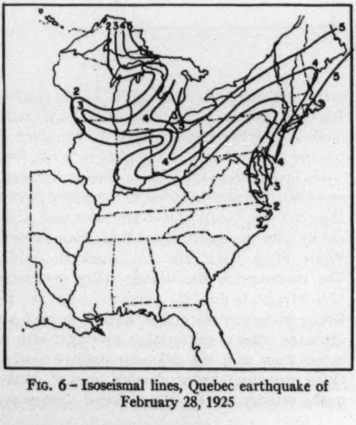


FIG. 6 - Isoseismal lines, Quebec earthquake of February 28, 1925

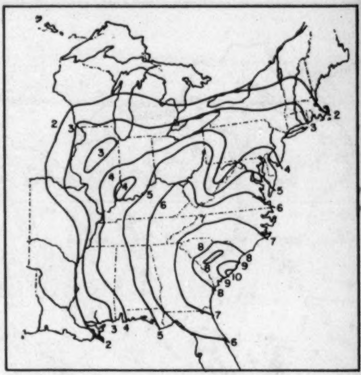


FIG. 7 - Isoseismal lines, Charleston earthquake of 1886

In the Appalachian region the fact that both the Piedmont shear zone and the belt of overthrusts and folds show continuing seismic activity as well as the development of cross structure earthquake alignments as in South Carolina suggests regional uplift, shearing, and warping. This appears to be substantiated by basement structures such as the Cape Fear arch and Salisbury embayment beneath the Coastal Plain, as well as the surface geologic features.

In the New England area activity is again noted in the boundary zone of a known tectonic element, the Adirondack massif. Earthquakes also occur in connection with the Taconic Fault, along the boundary of the Narragansett Basin, in the Boston Basin, in association with the Connecticut River and along on two and possibly three alignments in the crystalline rock area of New Hampshire and

Maine. The latter in part appears to be related to granitic intrusives. Since nearly all the tectonic elements in the New England area are involved, it would appear that the region as a whole is subject to stress. One cause here would be regional uplift because of isostatic rebound of the crust after melting of the Pleistocene ice cap. However, the fact that earthquake activity characterizes the entire Atlantic seaboard strongly suggest epeirogenic movement and perhaps shearing stresses throughout the Appalachian tectonic province.

To summarize the above, it appears that epeirogenic uplift is in progress over much of the country giving rise to earthquakes along older fractures and the boundary faults of major tectonic units. In some areas, as the western states, entire physiographic provinces appear to be behaving as a unit with little disturbance away from the boundary faults; in other areas, as the eastern seaboard, faults throughout the area appear to be activated. In the stable interior region activity appears to be associated principally with basement areas of uplift. There is one 'belt' of earthquakes which parallels the strike of the Appalachians and crosses from the head of the Mississippi embayment to the St. Lawrence River valley which while not related to known geologic structure does follow an axis of high seismic transmissibility. A similar zone is suggested running east-west from Iowa to Michigan. In the West Coast area the great number of earthquakes associated with the strike-slip movement on the San Andreas Fault and related systems makes it difficult to resolve how much epeirogenic uplift may be present. However, activity within the Sierra Nevada block and along its eastern boundary strongly suggest this unit is rising. Only in the Puget Sound depression, the Anadarko Basin and the Rio Grande valley of New Mexico is there any suggestion of local activity suggesting active subsidence outside of the Great Basin.

Focal depth relationships—In the introduction it was stated that most earthquakes in the United States originate in the crustal layer defined by the terrestrial section lying above the Mohorovicic discontinuity. This on the average is at a depth of about 35 km if seismic-blast studies of crustal thickness are accepted. If gravitational data are evaluated in terms of variations in crustal structure under the Airy theory of isostasy using auxiliary seismic data in both the oceanic and continental areas for control purposes, a somewhat different picture of crustal structure is obtained. Such an analysis of Bouguer gravity anomalies shows that the eastern half of the country has a crustal thickness of about 35 kms and the western half a mean value approaching 50 km. The mountain zones in both areas are characterized by local thickening. This picture of the continental crust is essentially the same as that developed recently by *Press* and *Ewing* [1957] from their analyses of Rayleigh wave phase velocity dispersion in the United States from distant earthquakes. In view of these apparent variations in crustal thickness and the fact that most continental earthquakes originate within about 30 km of the surface, the writer felt it would be instructive to see if any systematic relationship existed between the focal depth and thickness of the crust. To investigate this, the focal depths were computed for those earthquakes that were unusual enough either in terms of intensity on widespread effect to warrant the preparation of isoseismal maps by the U. S. Coast and Geodetic Survey. These depths were first grouped according to the areas of seismicity outlined earlier. In the case of California the area was first subdivided into sub-areas which it was thought might have differences on the basis of regional differences in geology. The California coastal area was divided into a northern sector, a central sector, and a southern sector. Southern California was further divided into two parts, the Mohave Desert area immediately south of the Sierra Nevada batholith, and the Mexican border area adjacent to the Gulf of Lower California and including northern Lower California. The area east of the Sierra Nevada batholith in California was considered along with western Nevada since both are in the same geologic province. For similar geologic reasons data for southern Quebec and Ontario were considered in a group that also includes northern New York. All of the New England states were considered as a unit. Another area considered as a unit was southeastern Missouri, southern Illinois and Indiana, western Tennessee and Kentucky, northern Mississippi and Arkansas.

The method of computing focal depth used is that based on the gravitational acceleration equivalents of the Modified Mercalli scale value at the epicenter and the epicentral distance to the I–II isoseismal contour. Since, as shown in Figures 6 and 7, the isoseismal pattern is usually far from regular, mean distance values were used. While the resulting focal-depth determinations at best are only approximations, the values obtained are very instructive and appear to give a real indication of variations in focal depth within and between areas. In general the depths obtained are somewhat greater than those determined from instrumental recordings, but not significantly different.

In some areas the depths obtained are remarkedly consistent. In other cases there are big differences, as in New England where there appears to be two distinct levels of activity: one at about 90 km and the other at 26 km. Here the explanation for the two levels of activity is suggested by the geologic associations. Earthquakes having a deep focus appear to be associated with granitic intrusive bodies and those at shallow depth with possible fracture zones. While New England represents an extreme case as regards separation of focal-depth levels, in other areas where the spread in levels is less pronounced, there is also a tendency for earthquakes to occur at discrete depths rather than on a random basis. In Table 2 the results are summarized as related to geographic distribution, and arranged so as to progress along strike of the various geologic provinces. In Table 3 the results are summarized as related to geologic provinces as a whole.

As the depth characterized with the greatest frequency of occurrence is also of interest, the data are summarized from this viewpoint in Table 4.

TABLE 2 – *Average depth of focus of earthquakes in the United States*

Area	Average depth of focus			
	km			
New England	89			26
New York-New Jersey			23	
South Carolina	57			
Louisiana				18
Tennessee-North Carolina		43	26	
Tennessee-Missouri-Illinois	58	36		
Ohio	65	43	26	
Quebec-Ontario-New York	57	40	21	
Montana		45	26	
Nebraska		47		
Texas-Oklahoma		50		
Texas-Mexico	70			
Utah		52		
Idaho	61	38		
Nevada			30	19
Mohave		43	30	
Baja California			29	15
Southern California			31	18
Central California		44	31	15
Northern California		46		21
Washington		41	33	

TABLE 3 – *Depth of earthquake foci in different geologic provinces*

Province	Average focal depth
	km
Appalachian crystalline complex, Coastal Plain	90, 60, and 25
Appalachian fold area	43 and 26
Gulf Coast area	18
Mid-continent stable shield area	60, 45, and 26
Southern Canadian shield area	60, 40, and 21
Rocky Mountain area	65 and 45
Great Basin area	43, 30, and 19
California Coastal area	44, 31, and 17
Puget Sound area	41 and 33

TABLE 4 – *Depth of earthquakes of greatest frequency*

Region	Predominant depth
	km
New England area	26
Appalachian Piedmont area	23
Stable Shield area	45
Rocky Mountain area about equal occurrences at	65 and 45
Great Basin area	30
California Coastal area about equal occurrences at	31 and 17
Puget Sound	33

From a study of these tables it appears four depths of earthquake origin are dominant: roughly 15–25 km, 30–35 km, 40–45 km, and 60–65 km. In any one area no more than three depths of origin occur. In general, coastal areas have shallower depths of origin for earthquakes than the continental interior. However, this is not an infallible rule since the Charleston, S. C., earthquake of 1866 had a deeper than normal focal depth for the Appalachian region.

It is seen that each seismic area has a distinctive depth pattern of earthquakes which may or may not extend into an adjacent seismic area. The distribution characteristic of the Pacific and western states, and which is not found elsewhere involves three depths: 15–20 km, 30–35 km, and 40–45 km. Activity is dominant in the shallow and intermediate zones along the Pacific Coast, but only at the 30-km level in the adjoining Great Basin area of block faulted structure. In the Rocky Mountains the characteristic depths are 45 km and 65 km with no marked preference as to frequence of occurrence. It may be significant that the deep focal depths here occur in the area of apparent maximum crustal thickness. In the stable shield area of the Midcontinent there are three depths of occurrence, 20–25 km, 40–45 km and 60 km. The level of greatest activity appears to be the 40- to 45-km zone. Except for the very deep earthquakes noted in New England in association with granite intrusions and the Charleston earthquake, a shallow focus depth of about 25 km characterizes the entire eastern seaboard. In the Appalachian Mountains proper the limited data suggest 43 and 26 km as characteristic values for this region.

From this admittedly qualitative study, which in the writer's opinion is the only kind justified in the present light of knowledge and available data, it appears that crustal thickness is somehow connected to the predominant depth of earthquake occurrence in the country. The thicker the crust, the deeper the depth of earthquake occurrence. In all areas the depth of predominant frequency appears to be somewhat above the base of the crustal layer. Where several discrete depths of earthquake occurrence characterize an area, the upper one never appears to be shallower than 12 km and usually is around 20 km. The deepest zone, except for the possible special case of granitic intrusives, appears to be about 60–65 km and this in all cases appears to be associated with the mantle rocks beneath the crust.

The implications of the above distribution and crustal relationships are not clear except in that crustal thickness is an apparent controlling factor. One possibility is that discrete changes in crustal rigidity such as are indicated by changes in crustal velocity associated with the Conrad and Mohorovicic discontinuities might influence the development of tensional and compressional strains in the boundary areas of a series of flexed crustal plates. The investigation of these relationships is being pursued further.

General remarks on observations—To try to explain the origin of the forces responsible for the observed earthquakes, their spatial distribution and variations in seismic activity with time is too hazardous an undertaking in view of present limited knowledge. However, a few remarks are justified concerning the relation of the observed activity to such factors as degree of isostatic equilibrium and variations in crustal structure both of which might play a role in causing earthquakes.

Relation of seismic activity to areas of isostatic unbalance—Since recent epeirogenic uplift appears to be a real phenomena over most of the western states and to a lesser extent in the Appalachian Mountain area from geologic data, there should be some independent indication other than earthquake activity as to whether this uplift still may be active. One approach to the problem is through a study of gravity anomalies. The Appalachian Mountain area is one of the seismic areas that is known from the gravity anomalies to be definitely out of isostatic equilibrium. The isostatic anomalies here indicate a marked deficiency in mass at depth which suggests a root much larger than is required to support the surface topography. Such an area could be expected to be subject to stresses leading to epeirogenic uplift. The adjacent Piedmont area on the other hand is an area of excess gravitational attraction. This suggests that this area in past geologic time was subject to marked uplift and that subsequent erosion of the surface arch created resulted in crustal thinning. Such a condition should induce forces leading to subsidence in order to establish isostatic equilibrium. The various summit peneplain surfaces in the Appalachian Mountain area confirm a history of continuing uplift in that area over a long period of time. The fact that the axis of Triassic arching in the Piedmont corresponds to that of the gravity maximum [*Woollard*, 1948] tends to confirm the idea of past uplift in that area. However, instead of subsequent subsidence recent studies of the basement configuration beneath the Coastal Plain [*Ewing* and others 1950] and [*Woollard* and others 1957] suggests considerable crustal warping not related to the gravity-anomaly pattern. In this connection it should be noted that the areas of current earthquake activity in the Piedmont-Coastal Plain region, particularly South Carolina and Virginia, do not correspond in position to the areas of basement warping. Further, only one minor earthquake has been reported over the positive Cape Fear arch although there is an alignment of earthquakes along the eastern boundary of the negative Salisbury Embayment (see Fig. 5).

While there are isostatic anomalies associated with many of the seismically active tectonic elements such as the Amarillo-Wichita uplift, Black Hills, Bighorn Mountains, and Rock Springs uplift, these are all areas of gravity maxima and appear to be uncompensated loads supported in large measure by the strength of the crust. Also, the geologic evidence indicates these areas are probably rising rather than subsiding. The only marked seismic area that is isostatically out of balance that appears to be sinking is the Puget Sound trough in Washington. This is an area with a pronounced gravity minimum that theoretically should be trying to rise rather than sink as it appears to have been doing. The gravitational evidence therefore cannot be used to make a firm case for either uplift or subsidence, and certainly there are many areas of marked local isostatic anomalies with which no earthquakes are identified. One such is the positive gravity anomaly area extending about 1000 mi southward from Lake Superior which is associated in part at least with synclinal structure and intruded basaltic lavas of Precambrian age. In the areas of greatest seismic activity, namely, California and Nevada as well as the area of marked recent epeirogenic uplift, the Colorado Plateau, isostatic compensation on the whole appears to be fairly well established with only local departures which appear to be associated with included structural units such as the Zuni and Defiance uplifts and the San Juan and Green River basins. The details on these gravity relations are not included here since they are being published by the writer elsewhere. The significant point is that current seismic activity cannot be related directly to the degree with which isostasy prevails.

Relationship of seismic activity to variations in crustal thickness—The relationship of earthquake focal depth to crustal structure has already been discussed. In this section the general problem of whether there is any correlation in terms of activity will be considered.

Where the crust is thick with presumably a high moment of inertia and greater rigidity than elsewhere, there may be an appreciable time lag in achieving hydrodynamic stability for changes in surface elevation brought about by erosion. Such a time lag would be expected to develop epeirogenic stresses leading to vertical uplift and associated earthquakes. It should also lead to negative isostatic gravity anomalies such as are observed in the Appalachian Mountains. The absence of any regional negative isostatic anomaly in association with an area of uplift as the Colorado Plateau implies equilibrium conditions with crustal thickening commensurate with the elevation. From studies of Bouguer gravity anomaly values by the writer this appears to be the case. However, seismic explosive blast studies by *Tuve* and *Tatel* [1955] in the Colorado Plateau as well as unpublished studies by other investigators in this area, indicate a crustal thickness considerably less than would be expected for equilibrium conditions. In fact, the thickness found is even less than that observed in the interior stable shield area of Minnesota and Wisconsin having a low elevation. It should be noted though that regional negative isostatic gravity anomalies in this part of the shield area do indicate a thicker-than-normal crust. This would suggest epeirogenic uplift stress in the area. However, this is an area essentially devoid of earthquakes. It is, however, an area that has been subject to continuous although perhaps intermittent uplift since early Paleozoic time. To explain the apparently anomalous relations it must be postulated that the rate of stress accumulation leading to uplift in the shield and accompanying earthquake activity is very slow. Presumably, when activity does take place it is pronounced and possibly similar to what is now being observed in the Missouri-Illinois-Arkansas-Tennessee border region which also lies in the stable shield area at the southern end of the Ozark uplift. Some of the biggest earthquakes in American history have occurred in this supposedly stable area.

Coming back to the Colorado Plateau area, it is of interest that seismic measurement of crustal thickness in other plateau areas based on explosive blasts give values no greater than observed in the lowlands and in all cases the values are incompatible with gravitational data, which suggest a thick crust. This has led *Hess* [1955] to postulate that the plateaus are rejuvenated through serpentenization of the subcrustal mantle rocks of ultrabasic composition. This process would result in subcrustal expansion forcing up the overlying crustal layer with no change in its thickness, explain the rejuvenation of plateaus, the associated earthquake activity and also satisfy both the Bouguer and isostatic gravity anomalies. While this is a very attractive hypothesis, it cannot be said to be proved. Cognizance also must be taken of the recent study by *Press* and *Ewing* [1957] using the velocity dispersion of Rayleigh waves as a means of determining crustal thickness. This technique gives values of crustal thickness in substantial agreement with that which the writer has computed from gravitational data. It leaves the problem of epeirogenic uplift of the plateaus and associated earthquake activity in the same indeterminate state as was reached from the study of gravity data alone.

Away from the plateaus in the lowlands and older tectonic areas, as the Appalachian Mountains, the observed values of crustal thickness from explosive blasts agree with the indications of the gravity data and the implications as to possible causes of tectonic activity in these areas. It therefore appears that there is no unique relation between variations in crustal thickness and degree of seismic activity.

Relation to theories of mountain building—While many theories have been advanced pertaining to mountain building [see *Eardley*, 1957, for a good review] they can be divided into three groups that might be expected to give a continuing history of associated seismic activity. One of these is represented by Hess's theory for crustal uplift because of periodic subcrustal expansion and contraction. This has already been commented upon. Another would be that of convection currents as proposed by *Griggs* [1939]. The third is the theory proposed by *Wilson* [1954] involving the formation of primary and secondary tectonic arcs with associated fracture zones through crustal contraction.

As the island arcs and associated seismic zones and gravity minima are used as pertinent evidence to support both Grigg's convection-current theory and Wilson's primary-secondary orogenic mountain zones, these relationships cannot be said to be proof for either theory. The identification of world serpentine belts with areas of orogenic activity and the island arcs by *Hess* [1937] however does appear to constitute evidence that these two physiographic features have something in common, and that the island arcs may represent a stage in the orogenic development of a mountain range. A significant and different feature of Wilson's theory is the development of opposing arc systems and associated connecting fracture zones. The writer would expect some indications of seismic activity along these associated fracture belts if they are genetically related to the orogenic mountain arcs. Such activity is conspicuously absent, which is surprising in view of the number of such postulated zones ringing the shield area on the east, south, and west. Further, except for the Appalachian Mountain area, the seismic belts of activity do not conform to the tectonic grain of the postulated orogenic mountain arcs as they do with the oceanic island arcs. While it can be argued that it should not be expected that early stress patterns as seen in the island arcs should persist in their later continental mountain counterparts, it seems strange that a single range of mountains as old as the Appalachians should preserve a relation of tectonic activity to structural pattern while much younger tectonic provinces of greater structural derangement do not show such a relationship. Perhaps in Triassic time the Appalachian earthquake activity followed the graben fault boundaries rather than the zone of thrusts similar to the relations observed with the trenches bordering the Rocky Mountain block today. The problem cannot be unequivocally answered, but it does appear there is little seismic evidence that can be offered in support of any one theory of mountain building being any more probable than another.

There is one bit of evidence though in connection with the Appalachian Mountains that does appear significant. This has to do with the question of whether the Appalachian Mountain system is continuous beneath the Mississippi embayment with the Ouachita Mountains of the same general age in Arkansas and Oklahoma. It is noted from Figure 5 that there is no continuous zone of earthquakes connecting the two and that the Appalachian zone of epicenters continues beneath the Coastal Plain along the same general northeast-southwesterly strike until they die out. These observations suggest that the two mountain systems are independent, although contemporaneous, and that they intersect with a 'T' relationship somewhere beneath the Mississippi-Alabama Coastal Plain.

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Gravity Survey of Ogden Valley in the Wasatch Mountains, North Central Utah

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Abstract—Ogden Valley is a northwest-trending valley in the Wasatch Mountains of north central Utah. From geologic investigations it is inferred that Ogden Valley is structurally controlled by normal faults along both the northeast and southwest margins. Gravity measurements in the valley indicate a fault with about 2000 ft of vertical displacement along the west margin of the valley. A fault with at least 1000 ft of vertical displacement is postulated along the east margin of the valley, and a smaller, buried fault is postulated within the valley. The maximum thickness of Cenozoic sediments and sedimentary rocks in the valley is estimated to be about 5000 ft.

Introduction—Ogden Valley, in Weber County, Utah, is a back valley lying about five miles east of the Wasatch front in north central Utah (Fig. 1). Its area of about 40 sq mi makes it one of the largest of the back valleys in the north central Wasatch Mountains. The valley trends northwesterly, slightly oblique to the north northwest strike of the Wasatch Mountains. It is completely enclosed on all sides except for one narrow drainage outlet, the Ogden River.

Ogden Valley is usually referred to as a 'structural trough,' implying that its present disposition is due primarily to normal faulting along its northeastern and southwestern margins, or to faulting along one margin only. However, none of the geologic maps of the area, from that of *Gilbert* [1890, p. 352] to that of *Lofgren* [1955, p. 70], indicates the location or trend of these faults.

A gravity survey was made to determine the probable presence or absence of these faults, and to delineate other major structural trends that may exist in the valley. It was also hoped that this investigation would aid in the study of similar structures, and be useful in studies of groundwater problems in the valley.

Geologic setting—The general geology of the Wasatch Mountain region has been reported in many early studies, most notable of which are those of *King* [1878] and *Gilbert* [1890]. *Blackwelder* [1910] first reported on the complexities of the thrust structures in the vicinity of Ogden Canyon. *Eardley* [1944] published a comprehensive report on the stratigraphy, structure, and physiography of the north central Wasatch, with special emphasis on the evolution of the Laramide and later structures. The U. S. Geological Survey, in cooperation with the State of Utah, has studied the unconsolidated sediments of Ogden Valley with emphasis on their hydrologic aspects [*Leggette* and *Taylor*, 1937; *Lofgren*, 1955; *Thomas*, 1945].

Except for a few Paleozoic sedimentary rocks cropping out along the west margin, Ogden Valley is enclosed on the north, east, and west by the Precambrian and Cambrian metasedimentary rocks of the Wasatch Mountains. These mountains rise as much as 4000 ft above the valley floor. Ogden Valley is separated from Morgan Valley to the south by a low, rolling ridge of stratified tuffs and marls of Tertiary age.

The present physiographic expression of Ogden Valley, of Morgan Valley to the south, and Cache Valley to the north is due primarily to late Laramide broad folding that trends north-south, and post-Laramide Basin-and-Range type normal faulting. *Schick* [1955] has shown the existence of normal faults younger than early Oligocene along the east side of Morgan Valley. *Adamson* and others [1955, p. 22] state that in Cache Valley "Post-Salt Lake group high-angle faults seem to parallel the mountain fronts. . . ." The Salt Lake formation is assigned a Pliocene (?) age. *Lofgren* 1955, p. 83] summarizes the evidence for normal faulting in Ogden Valley as follows: "Whereas the principal structure of Ogden Valley is due to folding, faulting, and general downwarping, which are known to have taken place mainly in Tertiary time, . . . fault scarps showing recent displacement are recognized in the valley. Along the west margin of the valley and paralleling the general trend of the structural trough, a scarp having several tens of feet of displacement is clearly defined. Although this scarp is somewhat modified by erosion, it is recent enough to be traceable in relief for several miles, and is evident along the base of the mountain front west of Liberty. Along this fault line arise several springs, which in the area west of Liberty yield sizable quantities of cold water of good quality. South and east of the large Liberty Springs, a series of small springs follows the base of the fault scarp. . . ." *Thomas* [1945,

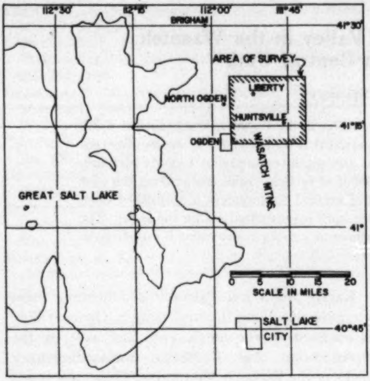


FIG. 1 – Index map of north central Wasatch Mountain region

p. 9], in correlating well logs in Ogden Valley, found evidence of displacement of about 25 ft within the unconsolidated sediments of the valley. He states that this displacement may be due "... perhaps because of displacement on a fault along the west margin of Ogden Valley, perhaps merely because of inaccuracies of the driller's logs."

Only one reference describing faulting along the eastern margin of Ogden Valley was found in the literature. In this reference *Gilbert* [1928, p. 57] states: "On the eastern margin of the valley there is a fault with throw to the southwest. . . ." Although the normal faulting of basin-and-range type throughout the north central Wasatch region is believed to range in age from late Eocene to Recent, it all seems to be related to a single subcrustal force active to the present time.

Field methods—One hundred gravity stations were established in Ogden Valley and immediately adjacent areas during the winter months of 1955–1956. A Worden gravimeter having a sensitivity of 0.09951 mgal per scale division was used. A standard looping method of making gravity observations was employed whereby a gravity base station was occupied three or more times a day for purposes of gravimeter drift control, and subsidiary drift checks were made on a few other stations throughout the day. In addition, repeat gravity observations were regularly made at other stations established earlier in the survey. These repeat readings show that the observed values of gravity are accurate to 0.02 mgal.

The survey was tied to the U. S. Coast and Geodetic Survey Pendulum Station 49 in Salt Lake City, Utah [*Duerksen*, 1949].

Elevation control was obtained primarily by means of bench marks and other points of known elevation found on the U. S. Geological Survey topographic quadrangle maps used in the survey. Eight elevations were interpolated from the contour lines on the topographic maps, and are believed to be accurate within four feet in the flat areas of the valley and within ten feet in the more mountainous areas.

A plane table and alidade was used to obtain elevations along the eastern margin of the valley. These elevations are accurate within four feet.

Reduction and presentation of data—Readings of observed gravity were corrected for drift of the gravimeter, for the latitude and elevation of each station, and for terrain effects. The latitude correction for each gravity station, based upon the international gravity formula of 1930, was obtained from tables of *Swick* [1942, pp. 61–63]. An elevation correction of 0.06 mgal per foot was used, corresponding to an average rock density of 2.67 gms per cm^3. Terrain corrections out to a radial distance of 5.2 mi from each gravity station were made using the U. S. Coast and Geodetic Survey tables [*Swick*, 1942, p. 68].

One thousand mgals have been added to the Bouguer values so that a gravity map with all positive numbers can be presented. By subtracting 1000 mgal from the values on the gravity map or profiles the Bouguer anomalies, corrected for terrain to the radial distance of 5.2 mi, may be obtained.

The relative gravity at each station is believed accurate to 0.3 mgal.

The Bouguer gravity field is shown on the gravity contour map (Fig. 2) in relation to the surface geology. The exposed rock types, generalized from the maps of *Eardley* [1944] and *Lofgren* [1955], are shown as Quaternary alluvium, Tertiary tuff and conglomerate, and Paleozoic and Precambrian bedrock. For the purposes of this gravity survey, bedrock is defined as representing the more dense pre-Cenozoic sedimentary and metasedimentary rocks, and does not include the less dense Cenozoic sedimentary rocks. Regional gravity effects, to be discussed below, are not removed from this map.

Two gravity and geologic profiles, whose positions are shown in Figure 2, are presented in Figures 3 and 4. After an assumed linear regional gradient was removed from the profiles, they were quantitatively examined to determine the most reasonable bedrock-Cenozoic interface that could account for the residual anomaly. A graticule, designed by D. C. Skeels [*Dobrin*, 1952, p. 98] was used to make the analysis. Because the inferred geologic profile is not infinitely long in the dimension perpendicular to the plane of the profile, it was necessary to apply an end correction factor [*Nettleton*, 1940, p. 117] to all the points along the profile where the gravity effect was determined.

In choosing a suitable density contrast between the bedrock and the Cenozoic sedimentary rocks, it was necessary to consider the densities of the bedrock, of the alluvium, and of the Tertiary tuffs and marls, as well as the compaction of the unconsolidated valley sediments with depth. Lists of densities for the common rock types are plentiful in the literature. For the Precambrian metasedimentary rocks that constitute the main part of the bedrock, an average density of 2.7 gm per cm^3 was assumed based on data of *Heiland* [1946, p. 72–84]. Similarly, a density of 2.2 gm per cm^3 was assumed for the unconsolidated valley sediments. This figure takes into account the compaction of the sediments to a depth of a few thousand feet, and the fact that they are, for the most part, water saturated.

In determining an average density for the Tertiary tuffs and marls, no suitable data were found in the literature. As an alternative, specimens of the tuff were collected from three outcrops south of Ogden Valley, and their density determined. The water-saturated densities of the tuff were found to range from 1.39 to 2.25 gm per cm^3; the average was about 2.10 gm per cm^3. The densities of these tuffs and marls will certainly increase with depth, owing to compaction.

Because of the similar densities of the unconsolidated valley sediments and the Tertiary tuffs and marls the writer feels secure in combining these two rock types for the purpose of analyzing the gravity data. These combined rock types are assigned an average density of 2.2 gm per cm^3. The density contrast between the pre-Cenozoic bedrock and the Cenozoic sediments and sedimentary rocks is about 0.5 gm per cm^3, and this figure is used in the graticule analysis. The primary features of the Bouguer gravity anomaly are therefore attributable to the primary density contrast existing between the pre-Cenozoic metasedimentary rocks and the Cenozoic sedimentary rocks.

GEOLOGIC INTERPRETATION OF THE DATA

General features—The gravity anomaly (Fig. 2) comprises a closed gravity low centering over the sedimentary rocks of the valley, and rapidly increasing gravity values along the bedrock margins of the northeastern and southwestern parts of the valley. These steep gravity gradients indicate the existence of a steep bedrock-Cenozoic interface beneath the valley.

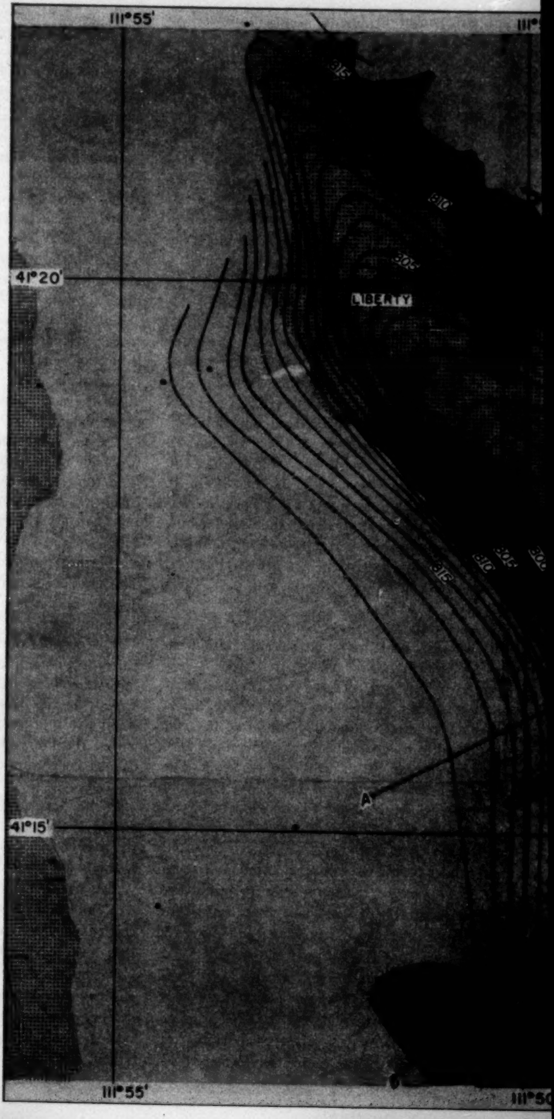
The northwestern and southeastern margins of the valley are characterized by comparatively low gravity gradients. These indicate a gentle rise of the bedrock surface beneath the valley to the places where it crops out around the valley. There is no geological or geophysical evidence for the existence of faults or other steep bedrock slopes along the northwestern and southeastern margins of the valley.

The fact that values of the gravity along the west side of the valley are about 15 mgal higher than those along the east side of the valley indicates the existence of a regional gradient on which the Ogden Valley anomaly is superposed. From Figures 3 and 4 the gradient is seen to decrease to the northeast at a rate of about 1.3 mgal per mile. This gradient is too large to be caused entirely by distant topographic effects, and must have a more profound cause.

It is possible that this regional gradient in the part of the mountains surveyed indicates a regional thickening of a lighter density crustal material underlying the Wasatch Mountains in Utah. It could also indicate horizontal variations of density within the Precambrian and Paleozoic rocks. No definite conclusion can be reached on the basis of this survey.

In the quantitative analysis of profiles A-A′ and B-B′ this regional gradient is subtracted from the Bouguer anomaly values, and the residual anomaly analyzed.

Analysis with graticule—The positions of profiles A-A′ and B-B′ were chosen for the quantitative graticule analysis in the hope that they would give the most meaningful interpretation of the pre-Cenozoic configuration beneath the valley. Because of the few stations established on bedrock along the northeast margin of the valley, it was necessary to take the profiles virtually next to each other in this region, and then to skew them apart in the south-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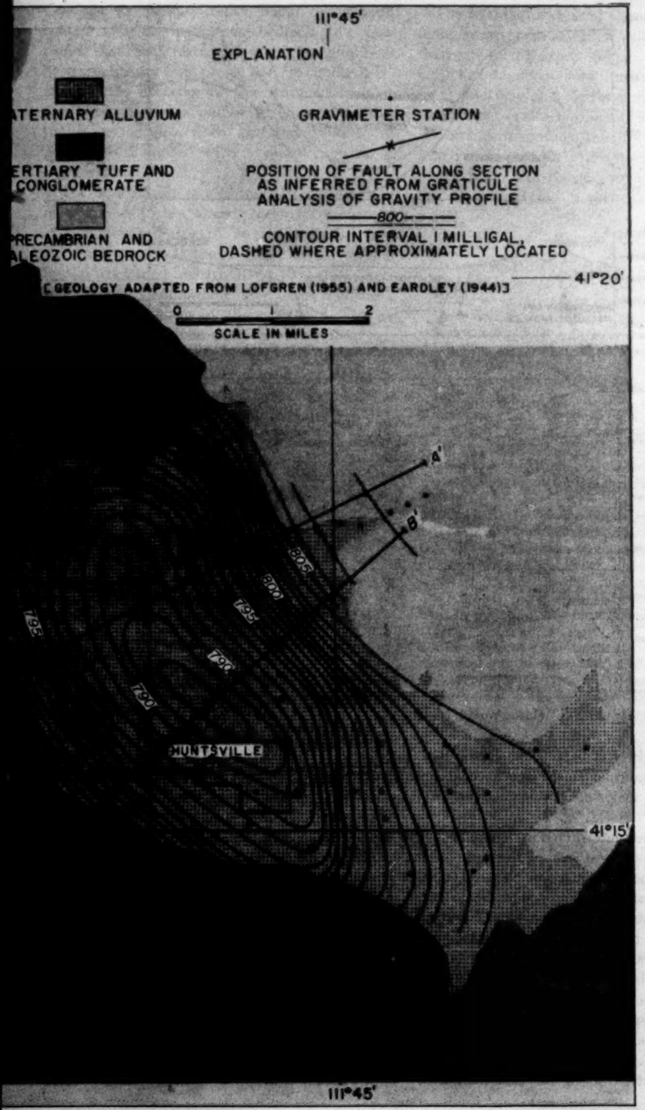
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EXPLANATION
ATERNARY ALLUVIUM
ERTIARY TUFF AND CONGLOMERATE
PRECAMBRIAN AND ALEOZOIC BEDROCK
GRAVIMETER STATION
POSITION OF FAULT ALONG SECTION AS INFERRED FROM GRATICULE ANALYSIS OF GRAVITY PROFILE
800
CONTOUR INTERVAL 1 MILLIGAL, DASHED WHERE APPROXIMATELY LOCATED
41°20'
[GEOLOGY ADAPTED FROM LOFGREN (1955) AND EARDLEY (1944)]
0 1 2
SCALE IN MILES
A'
B'
805
800
795
795
790
790
HUNTSVILLE
41°15'
111°45'

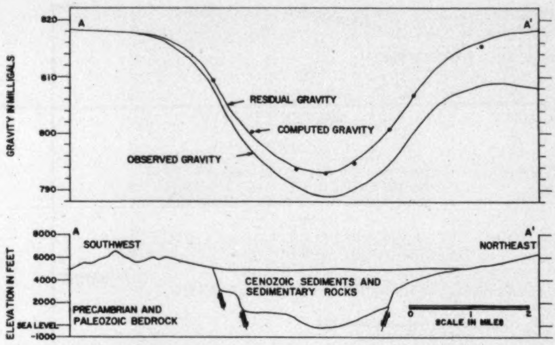

FIG. 3 – Geology and gravity anomaly along Profile A-A′

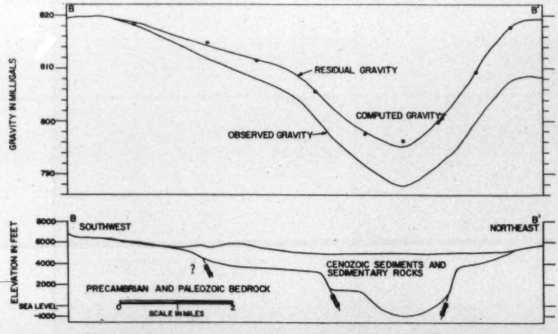

FIG. 4 – Geology and gravity anomaly along Profile B-B′

west part of the valley. The fact that profile B-B′ is not quite perpendicular to the gravity contours should not have a major effect upon the interpretation.

Profile A-A′ is best interpreted by assuming two faults along the southwest side of the valley and one fault along the northeast side. The westernmost fault in section A-A′ is exposed at the surface, so there is no doubt of its existence. The gravity analysis indicates that it has a vertical displacement of about 2000 ft. About 2000 ft east of this fault, and buried beneath about 2000 ft of Cenozoic sediments and sedimentary rocks, another fault having a displacement of about 1500 ft is postulated. This buried fault also manifests itself across profile B-B′.

The fault postulated along the east margin of the valley in profile A-A′ is buried beneath approximately 1500 ft of Cenozoic sedimentary rocks, and has a vertical displacement of about 1500 ft. The total vertical displacement along the two western faults in profile A-A′ is about 3500 ft.

The interpretation of profile B-B′ is similar. The westernmost fault in profile A-A′ is not, however, definitely indicated by the gravity data along profile B-B′. Instead, there is only a slight but noticeable thickening of the Cenozoic sedimentary rocks in the western third of profile B-B′. If this fault continues southward to profile B-B′ its vertical displacement in the region must be small, probably less than 500 ft. For if a normal fault of major proportions does exist nearly perpendicular to the plane of profile B-B′ in this area it would appear in the gravity data because the less dense

Cenozoic sedimentary rocks would be in fault contact with the more dense bedrock. It is concluded that the displacement of this marginal fault decreases greatly from profile A-A′ to profile B-B′. Because the existence of this marginal fault in the latter profile is only inferred, and neither proved nor disproved by the gravity data, its position is indicated with a question mark in Figures 2 and 4.

The buried fault east of the westernmost fault in profile A-A′ has already been mentioned as extending southeastward to profile B-B′. The easternmost fault in profile B-B′, similar to that in A-A′, is buried beneath about 1000 ft of Cenozoic sediments and sedimentary rocks, and has a vertical displacement of about 2000 ft. The assumed density contrast of 0.5 gm per cm^3 used in the graticule analysis indicates that the deepest accumulation of Cenozoic sedimentary rocks in the valley is about 5500 ft. It may be greater or less than this, depending on whether the true density contrast is less or greater than that assumed.

Slightly west of the deepest part of the Cenozoic sedimentary rocks in both profiles an abrupt change of the bedrock slope is indicated by the quantitative interpretation of the gravity profiles. This sharp change in slope may be the result of faulting, of erosional processes that occurred before deposition of the Cenozoic sedimentary rocks, of the broad north-south folding known to have occurred in this region in early Tertiary time [*Eardley*, 1951, p. 325–336], or a combination of these processes.

The positions and displacements of the faults and the sharp change of bedrock slope noted above in profile B-B′ correlate well with those in A-A′. The vertical projection to the surface of the upper edge of the footwall portion of each fault, or the upper edge of the sharp change in bedrock slope, is indicated by × along profiles A-A′ and B-B′ in Figure 2.

Conclusion—With the assumptions made in the analysis of the gravity profiles it would be difficult to make a greatly different and still geologically reasonable interpretation of the gravity data. It would be possible to substitute a series of step faults of small individual displacements for the large normal faults of thousands of feet of displacement postulated along both margins of the valley, but the writer feels it would be misleading to attempt to force from the data an interpretation that is not warranted by the available geophysical or geological evidence.

The 5000-ft thickness of Cenozoic sediments and sedimentary rocks in Ogden Valley is much greater than one might expect for an enclosed valley of only five to seven miles maximum width. This great thickness and the large displacements along the normal faults forming this graben structure are of such magnitude that they should be taken into consideration in future studies of the evolution of the Basin and Range Province in general, and the Wasatch region in particular.

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(Communicated manuscript received August 11, 1958.)

Letter to the Editor

Photogrammetric Flow Measurements on Antarctic Glaciers

During 1957 measurements of the rate of ice flow were made by conventional ground survey methods along several stretches of coast within 50 mi of the main base of the Australian National Antarctic Research Expeditions. It seemed highly desirable to measure also the velocity of certain fast-moving ice streams which were situated at greater distances from the base, but for logistic reasons it was not possible to put ground parties in these areas, which in any case presented great difficulties of access and control for ground survey.

Measurements made by triangulation on a small glacier tongue suggested that the movement of the big ice streams was probably sufficiently rapid to permit measurements to be made by aerial photogrammetry over a period of a few months. The most important prerequisites were fixed control points and ground marks on the moving ice.

Oblique photographs taken earlier showed numerous rock outcrops and skerries along the coast and it was found that fixed rock control points could be located for each of the glaciers (the Jelbart Glacier in MacRobertson Land and the Dovers and Hoseason Glaciers in Kemp Land). Moreover, there was photographic evidence that configuration of crevasse patterns at the seaward extremities of these glaciers did not change over the period of one year, so that crevasses or melt channels could be utilized as ground marks.

Photographic runs, using only the vertical camera of a trimetrogon installation, were planned so that rock islands and outcrops would be included, and the first flights were made in early August 1957. A D. H. Beaver aircraft was used and the runs were made at a true altitude of 10,000 ft, thus giving a scale of 1:20,000 on photographs taken with a six-inch focal length camera. The runs were repeated in December 1957 and the two sets of photographs were brought back to Australia for examination.

The radial-line method was used to plot fixed control points on rock, and a number of selected common points on the glacier surface were then mapped to the same scale. Comparison of the two positions of corresponding points gave a direct measure of the displacement which had occurred between the two runs. It was found unnecessary to use more than one strip of photos for each glacier, so that only 12 to 16 photos required plotting for each set of measurements.

The period which elapsed between the two sets of surveys was 120 days, and measured displacements at the scale of the prints ranged from 0.05 to 0.68 inch, corresponding to velocities of 8.3 to 113 inches per day. Although no independent checks are available, the transverse velocity distributions given by the measurements conform to those which might be expected from established theory. Full results will be given elsewhere.

The method could easily be adapted to measure the movement of the big inland ice streams so long as rock control points and reasonably snow-free ice surfaces are present. As long time lapses are undesirable, the method as outlined is probably not suitable for use on glaciers having mid-stream surface velocities less than 15 inches per day. Flights would be best carried out at the end of one summer and again at the beginning of the next summer, so that the melt-stream patterns would undergo no change. For inland work use of the radar altimeter would be essential.

MALCOLM MELLOR
Antarctic Division, Department of External Affairs, Melbourne, Australia.

Discussion of "Needed Research in Sedimentation"

BY W. C. ACKERMANN

[*Trans.*, **38**, 925–927, 1957]

G. C. Amstutz (Department of Geology, Missouri School of Mines and Metallurgy, Rolla, Mo.)—An old Latin adage says, "Nature has made judges of all of us, but only a few artists." In this spirit it is that I would like to comment on Ackermann's interesting programmatic outline.

The present writer recently attempted to tackle one of the problems involved in desert sand sedimentation, not mentioned by Ackermann because he deals mostly with sedimentation in water, and has set up a morphogenetic function relating, tentatively, the shape $S_{x,t}$ of a sand grain at a certain place x and a certain time t to some ten factors influencing this shape. Ackermann does not mention the great amount of fine research done with regard to the role of size and shape in sedimentation.

It may be unjust to judge a man's work from a brief article. However, none of the 82 references in this and the accompanying seven papers of the Symposium on Watershed Erosion and Sediment Yields is taken from foreign literature. If this is a true picture of the work done by this Symposium I want to add a comment and a suggestion.

After the Russians sent up their sputniks we could read in most newspapers that we should not waste time in finding a better approach to many important scientific problems. As one conversant with several foreign languages, my comment is: Almost half of the average papers published in the United States are out-dated by results published previously in foreign journals, or they repeat in part what others have done equally well or better, or they are incomplete in comparison with foreign work. Often they present ideas as new which are already well known in foreign literature.

This causes us to lose time and perhaps the race. Of course it is desirable to repeat measurements for the purpose of strengthening the evidence or for other purposes. But too often a student or research worker has little idea what has been done in his field of interest in other countries. This is because of lack of knowledge of other languages. We know that the sputnik scientists were completely up-to-date on the last published advances in our country in metallurgy, physics, mathematics, and other fields important in missile research, and that many of our 'pure research publications' have helped them. Why? Because they read and use them and do not repeat our measurements and calculations if they are good.

We must decide whether we want to stick to the illusion that everything in the United States is biggest and best, or whether we will spend money for translations or time for learning a language. The fact that none of the 82 references in the eight papers of the above Symposium refer to foreign literature is alarming.

My suggestion: Much careful, extensive, and meticulous work has been done in foreign countries in the field of experimental sedimentation research and observations in nature. For lack of space I offer only one example from Switzerland's Federal Institute for Hydraulic Research. Papers by Lütschg, Meyer and others show how long ago much work was started. Probably the best international summary on sedimentation was written by Paul Niggli (Gesteine und Minerallagerstätten, Birkhäuser, Basel, vol. 2, 1949).

William C. Ackermann (Illinois State Water Division, Urbana, Ill.; Author's closure)—Amstutz has for some reason chosen to address this author whose paper was on the general subject of sedimentation and a part of the symposium noted. Although his tone is distinctly critical, some personal satisfaction is derived from the fact that little of it is directed at the author whose references in the short paper were two in number. He points to the general failure to include references to much fine foreign work which has been accomplished and reported. This is probably justified, although my paper does not attempt to summarize previous work, either foreign or domestic. It was aimed at research needed to solve problems which are developing primarily as a consequence of action programs in the United States.

Amstutz moves on rather quickly to scold the entire panel and finally all scientists in this country for the fault of not reading foreign literature. He states that more than half of the average papers published in the United States are either outdated, repeat the work of others, or are incomplete. This is a shocking situation, if true.

Whatever the proportion of originality in this country, most scientists in the United States will agree with the discusser that we in general are not sufficiently acquainted with work in other countries. Ways must be found to bring translations in both abstract and complete form to our scientific workers. This author believes this will be done.

Discussion of "Longitudinal and Transverse Diffusion in Granular Deposits"

BY G. DE JOSSELIN DE JONG

[*Trans.*, **39**, 67–74, 1958]

J. A. Cole (Department of Geodesy and Geophysics, University of Cambridge, Cambridge, England)—The writer finds the paper most valuable, because he [*Cole*, 1957] has made experiments with columns of granular material, basically similar to those described by the author, in order to determine the relative importance of: Effect (a) radial molecular diffusion in each pore combined with a velocity gradient across the pore, and Effect (b) the geometry of the pore system, in producing a longitudinal dispersion of an injected substance.

The author mentions Effect (a), but makes the assumption that it may be neglected if the pore section is small enough. Though valid, such an assumption is not often realized, as the following numerical examples illustrate. *Taylor* [1953, 1954ab] has shown that the diffusion coefficient D_S of Effect (a) with streamline flow in straight cylindrical tubes of radius a is

$$D_S = a^2 v_0^2/48\, D_m \qquad (26)$$

when

$$4L/a \gg v_0 a/D_m \gg 6.9 \qquad (27)$$

L being the distance along the tube in which the concentration of the injected substance has an appreciable gradient, and is approximately equal to 4 σ_Z. The first condition in (27) can easily be met by using large enough values of Z. Figure 6 is a presentation of D_S versus v_0 on a log-log graph, for two values of a. Where the two lines are broken the second condition in (27) does not hold, and (26) is only an approximation. In applying (26) to granular materials, which do not have cylindrical pores as a rule, one uses a mean pore radius (see $\bar{a}$ below) in computing D_S. The random orientation of the pores results in one's observing not D_S, but $D_S/\xi^2 = a^2(\langle z\rangle/\langle t\rangle)^2/48D_m$, where $\langle z\rangle/\langle t\rangle = v_0/\xi$.

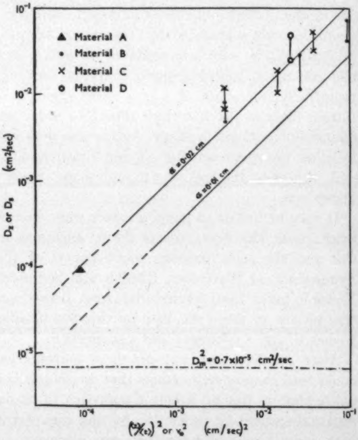

FIG. 6 – Comparison of D_s observed in the granular materials listed in Table 1 with theoretical values of D_s.

TABLE 1 – *Properties of porous columns*

Material	Composition of material	d	p	ā
		cm		cm
A	Glass beads	0.020	0.385	0.0086
B	Glass beads	0.047	0.35	0.018
C	Glass beads	0.027	0.33	0.0105
D	Clean quartz sand	0.034	≈0.33	≈0.013

Clearly a line corresponding to D_S/ξ^2, for a given value of a, plotted versus $(\langle z\rangle/\langle t\rangle)^2$ is coincident with that of D_S versus v_0 for the same value of a.

The author gives for his measurements in a glass-bead column, $\sigma_Z = 0.6$ cm when $Z = 17.0$ cm and $\langle z \rangle / \langle t \rangle = 0.55$ cm/min $= 0.0092$ cm/sec. Accordingly $D_Z = 0.6^2 \times 0.0092/34$ cm^2/sec $= 9.6 \times 10^{-5}$ cm/sec.

This value of D_Z is shown (as the point for Material A) on Figure 6. Also shown are some values of D_Z in columns of glass beads and of clean quartz sand, which were obtained by the writer. Materials A, B, C, and D have the properties specified in Table 1, where d = mean grain diameter, p = coefficient of volume of porosity, and $\bar{\bar{a}} = (d/2)[p/(1 - p)]^{\frac{1}{2}}$ = the mean radius of the pores, approximating the polyhedra to spheres.

These values of $\bar{\bar{a}}$ correspond to values of D_S/ξ^2 which are far from negligible. In Material A, the case quoted by the author, it is likely that Effect (a) was appreciable (one tenth of the observed D_Z say). In the other examples Effect (a) was of major importance, amounting to a quarter of the observed D_Z in Materials B and D, and almost all thereof in material C.

In contrast to the above laboratory experiments, the writer [*Cole*, 1957] also made field experiments with tracers flowing in chalk aquifers. These showed values of D_Z some hundred times greater than would have been expected from Effect (a) alone, and it was presumed that Effect (b) was predominant. Even that was not certain, owing to possible chemisorption effects within the aquifer.

There is thus scope for development of a fuller treatment of longitudinal dispersion in granular materials. Besides Effects (a) and (b), such a treatment would ideally include the work of *de Vault* [1943], *Thomas* [1944], and *Goldstein* [1953] on chemisorption processes in porous columns.

Further laboratory work would profit by the determination of the pore radii in the granular material, by measurement of its water content oyer a range of negative pressures [*Foster*, 1948].

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G. de Josselin de Jong (Laboratorium Voor Grondmechanica, Postbox 69, Delft, The Netherlands, Author's closure)—In his discussion Cole gives further information on the deviation from our theory to be expected in experiments for which the basic assumption of piston flow in the elementary canals is unsatisfactory so that the influence of holdback can not be neglected. According to the conception of *Van Deemter* and others [1955], this holdback amounts to $H = 0.02$ in the test described, because the factor $(D_m t/a^2)^{\frac{1}{2}} = 11$, where D_m = molecular diffusion = 0.7×10^{-5} cm^2/sec, t = time to cover the distance 4 σ_z with mean velocity = 2.4 cm/0.0092 cm/sec = 270 sec, and a = radius of pores = 0.004 cm.

For the interpretation of the test results in the article this amount of holdback was considered as negligible. According to his theory Cole obtains a somewhat larger influence about one tenth of the longitudinal diffusion.

As the principal point of our considerations was to show the interrelation between longitudinal and transverse diffusion and the possibility to describe these two phenomena in one mathematical expression, the influence of holdback and molecular diffusion both were omitted in the theoretical considerations for simplicity's sake. But we do agree that these two effects and the chemisorption as mentioned in the discussion may have an overwhelming influence in certain circumstances.

In order to show the phenomenon of longitudinal and transverse diffusion we add here some photographs of a Christiansen filter (Fig. 7). This is a deposit of crushed optical glass (grain diameter 0.42 to 1.19 mm) saturated with a solution of NH_4J in water of such a concentration that both refraction indices of grains and pore liquid are equal for sodium light.

As the light is not dispersed by deviation of its direction at the interfaces of grains and liquid the system becomes perspicace. (We are indebted to the Shell Laboratory, Amsterdam, for this device.)

The pore liquid runs vertically through the

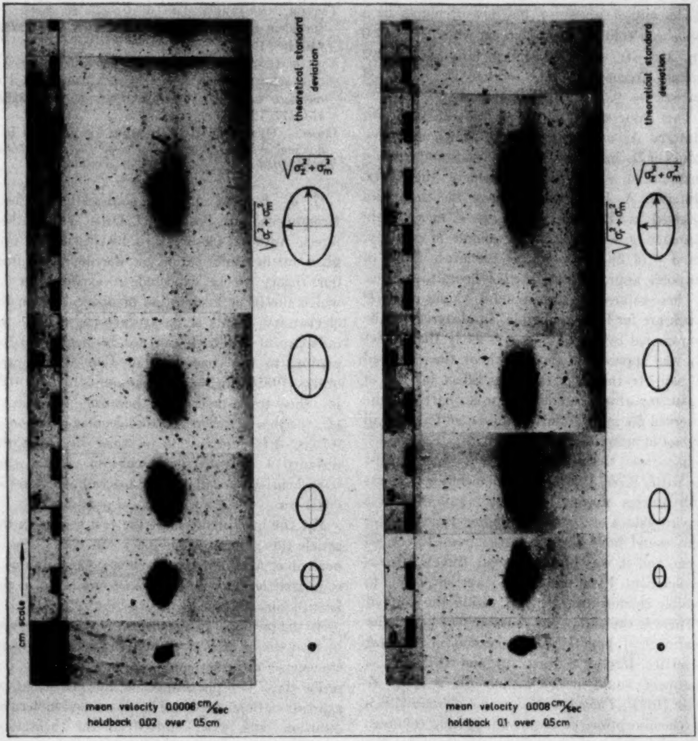
theoretical standard deviation
$\sqrt{\sigma_z^2+\sigma_m^2}$
$\sqrt{\sigma_r^2+\sigma_m^2}$
cm scale
mean velocity 0.0008 cm/sec
holdback 0.02 over 0.5cm
theoretical standard deviation
$\sqrt{\sigma_z^2+\sigma_m^2}$
$\sqrt{\sigma_r^2+\sigma_m^2}$
mean velocity 0.008 cm/sec
holdback 0.1 over 0.5cm

FIG. 7—Christiansen filter showing longitudinal and transverse diffusion

deposit. An analine dye is introduced with an injection needle. The molecular diffusion of the dye is about $D_m = 10^{-5}$ cm² sec. The photographs show the dispersion originated at two velocities, 0.0008 cm/sec and 0.008 cm/sec, which induce a holdback over a distance of 0.5 cm of respectively 0.025 and 0.10. The standard deviations originated by molecular diffusion in combination with longitudinal and transverse diffusion as computed from the theory are added in the figure for comparison.

At the lower velocity the elongation of the standard deviation ellipsoid is principally determined by the longitudinal diffusion, while at the higher velocity the influence of the holdback enters into the observation.

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Discussion of "Evaporation Study at Silver Lake in the Mojave Desert, California"

BY HARRY F. BLANEY

[*Trans.*, **38**, 209–215, 1957]

N. J. Cochrane (Alliance House, Caxton Street, Westminster, London, S.W.1., England)—Blaney's paper is the latest of his invaluable contributions to large-scale evaporation studies. The fact that the shallow Silver Lake sensibly dried up during the period of observation might suggest that the data are not necessarily representative of the evaporation from a perennial lake of substantial depth in a similar situation. Nevertheless if we take the mean relative humidity H_r at say 55 pct, the mean wind speed U at ten meters as, say, seven miles per hour, the mean annual temperature T as 70°F, the writer's formula

$$e = \frac{T^2}{100} \times \sqrt[3]{\frac{U+3}{20H_r}} \times \left(\frac{60}{H_r T}\right)^{0\cdot 8}$$

suggests a value of 72 inches for the evaporation from an open lake in the circumstances.

Harry F. Blaney (Agricultural Research Service, Los Angeles, Calif.; Author's closure)—The conclusion by Cochrane, that evaporation from the shallow Silver Lake might not necessarily be representative of the evaporation from a perennial lake of substantial depth may be correct. However, these data can be used to estimate evaporation from many of the dry lakes in western United States which are occasionally filled with water during years of excessive precipitation and runoff.

No doubt the lower annual evaporation of 72 inches which Cochrane obtains from his empirical formula (using Silver Lake climatic data) is for a perennial lake. The average annual evaporation loss from Salton Sea, California, located in a somewhat similar climate to that of Silver Lake, was estimated [*Blaney*, 1955] to be 73 inches.

Cochrane [1956] should have cited the paper with the description of his formula for estimating lake evaporation. This formula was developed after a study was made of some 80 records from evaporation pans spread widely over the world. At some sites climatic data were also available. Cochrane indicates that evaporation from open water surfaces should be a direct function of temperature and wind speed and a function of relative humidity in this formula which is designed to cover a wide range of climates. Also, that his formula gives results within ±10 pct.

The author has found the formula $e = kf$ to be useful not only for computing monthly evaporation from desert lakes, but also for estimating evaporation at high altitudes during the winter months when the water in pans freezes and no measurements of evaporation can be made. [*Blaney*, 1956].

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Discussion of "Problems Encountered in the Utilization of Ground-Water Reservoirs"

BY RAPHAEL G. KAZMANN

[*Trans.*, **39**, 94–99, 1958]

Harold Conkling (448 South Hill St., Los Angeles 13, Calif.; received April 14, 1958)—Kazman has made an interesting discussion of the problems encountered in utilization of ground-water reservoirs. It is just now becoming a problem which engages the attention of engineers in the humid areas of the United States but which, in some parts of the more arid regions has been recognized for at least the last 30 yr. Not only has it been a recognized problem but it is one which has been solved in some cases and will finally be solved in all.

In California it rains in winter and does not rain in the growing season. In addition, there is a long 'cyclic' variation in precipitation. Southward from the latitude of San Francisco the perennial discharge of streams becomes progressively smaller with distance. In the region generally known as Southern California, discharge of the streams in summer is almost non-existent. The region is arid. At least a century ago in this more arid portion of the State and along the coast northward, the sustained discharge had all been put to use.

A few years before the turn of the present century, wells for an irrigation supply began to be drilled in the alluvium deposited in the valleys by these same streams and charged by percolation from their winter floods. A supply, thought then to be inexhaustible, was thus tapped and the race was on. In another few years the safe yield of some of the basins was overdrawn but because of large excess capacity of the underground reservoirs, recognition of this did not come until many years afterward. The 'safe yield' means the annual yield which can be sustained throughout a period of long-time average recharge of the underground reservoir without cumulative recession of water-table. In other words it is the long-time average annual recharge.

As stated, cyclic as well as annual variation in discharge occurs. In Southern California the 'cycles' have averaged 28 years in length. Reservoir capacity five to eight times safe yield is required to iron out the variations, and generally more than that exists in the alluvium of the valley. The long cyclic rise and fall of the water table obscures the facts as to overdraft or sufficiency. Furthermore, no techniques were available for ascertaining the existence of and determining the amount of the overdraft.

About 30 yr ago, with funds appropriated by the State Legislature, techniques for ascertainment of and evaluation of overdraft were developed by State personnel but the first of such evaluations was not completed until some 15 years after the first overdraft began. In another ten years or so, Colorado River water was imported and the situation is being slowly rectified.

In the intermountain states the same problem that faced the water users of the southern half of California, began to trouble the underground water users some years later than their recognition in California. In these states not much progress has actually been made in their solution. Farther east in the Great Plains, aridity decreases and small local problems, such as described by Kazmann, exist along the streams. Over most of the area not near streams there is no problem. Underground water in commercial quantities is simply mined. Recharge is insignificant.

To this writer, the technical difficulties involved in the planned utilization of underground reservoirs do not appear great, at least in the case of those situations which he has encountered in his practice, but in many cases it is impossible to put such plans into effect until the situation has become so difficult that the majority of water users has realized that the 'inexhaustible' underground supply does not exist. No amount of persuasion is effective, nor could a consultant take time for such persuasion. Nor could he ethically pursue such a course. Events are the best persuaders.

H. W. Thoms (Edificio Monte Avila, Caracas, Venezuela; received May 23, 1958)—According to *Science*, the Population Reference Bureau has reported that "water shortages are now a national problem," and the United States "might not have enough of the precious mineral to go around" in the not-too-far-distant future. This observation is of world-wide application, and it seems only logical to develop underground reservoirs to the utmost wherever they exist. Hence, Kazmann may soon find it much easier to interest the public in projects designed to solve the problem, even though it may involve the organization of a recharge 'district.'

In Figure 2 the contours show the piezometric surface in the lower aquifer higher than in the upper aquifer, while in Figure 4 the schematic cross section shows the opposite condition. Does Figure 2 represent the original conditions in the two aquifers rather than those obtaining under the present development?

Raphael G. Kazmann (Stuttgart, Ark.; Author's closure)—Conkling's discussion, based on a wealth of ground-water experience in California, is a most welcome supplement to the original paper. The need to have reservoir storage equal from five to eight times the average annual recharge in order to maintain an offtake approximately equal to the average recharge is most significant. In a concrete fashion it puts emphasis on the phrase, "aquifiers are not subject to evaporation losses."

If reservoir capacity ample for the carry-over of water for periods up to eight years is needed, the water-costs of evaporation from surface reservoirs can be approximately evaluated. In the Southern California–Arizona area the net annual evaporation ranges from about 90 inches/yr at Phoenix to about 30 inches/yr at San Diego [*Meyer*, 1942 Appendix, pp. 39 and 46]. For purposes of illustration assume 42 inches/yr as the average net evaporation to be expected from a reservoir constructed in that region. Then the El Capitan Reservoir (surface area about 1500 ac) which is designed to carry over water from year-to-year (located on the San Diego River which has a mean annual flow of about 25,000 acft/yr) can be expected to lose approximately 5000 acft/yr, 20 pct of the average annual flow, to evaporation alone. Thus a ground-water reservoir of equal capacity could supply a firm offtake 20 pct higher than that of El Capitan. In a water-scarce area, where the value of water approximates $80 per acre foot, this advantage would be worth $400,000 a year. Even more important is the availability of the last 20 pct of the water supply, where no economically attractive alternate exists. Sea-water conversion still has as its goal the production of water at $300 per acre foot. At Lake Mead the evaporation rate is estimated at six feet per year or, for the 146,000 acres of lake surface, 876,000 ac ft/yr. Potentially replenishable ground-water reservoirs of the equal storage capacity (about 30 million acre feet) are not unusual in the southwest, but they are not burdened with that rate of loss.

Thus Conkling's words serve to emphasize, in quantitative terms, the need for fullest utilization of ground-water reservoirs. And this, in turn, implies the absolute necessity of developing an economical and effective method of ground-water recharge in the near future.

Thoms' remarks on the logic of ground-water development are fully shared by the writer: The precise timing of the necessary research will probably depend more upon the occurrence of actual water shortages than any other single factor.

Until 20 or 25 yr ago the artificial changes in river regime or weather were generally so small as to be negligible in the design of water-supply structures. More recently it has been necessary to take such changes into account in a minor way. Within the next 25 yr it may well be that plans of public and semi-public and private organizations, with regard to water control or use, will be almost as important as the long-term hydrologic observations made by the Weather Bureau, the U. S. Geological Survey and other fact-finding agencies. This paper is an attempt to call attention to this trend by citing a specific example: the regime of the Mississippi River at St. Louis.

Thom's interpretation of the illustrations contained in the original paper is correct and the writer regrets that the illustrations were not captioned more clearly.

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Discussion of "Upper and Lower Frequency Curves for Peak Rates of Runoff"

by W. D. Potter

[*Trans.*, **39**, 100–105, 1958]

W. T. Wilson and *D. M. Hershfield* (U. S. Weather Bureau, Washington 25, D. C.; received May 7, 1958)—The author has noted the frequent occurrence of non-linearity in stream-flow data as usually plotted on extreme-value probability paper, and has suggested fitting these data with two straight lines, crossing at the five-year return period. This is in contrast to the usual practice of fitting a straight line, or of using a curve (which could be a straight line on some other kind of paper). It seems remarkable that the two lines should cross at five years, instead of 3.34 years or some other return period, and that they should all cross at about the same return period.

It seems remarkable also that 69 streams, having a wide variety of physiographic and climatic

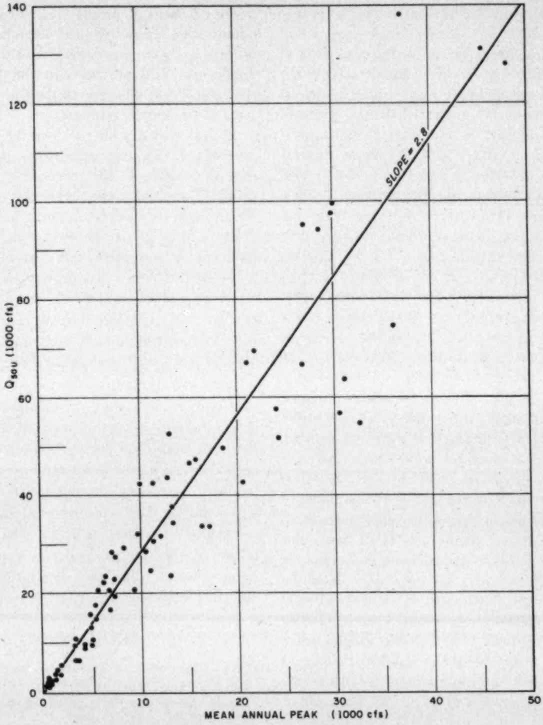

FIG. 7 – Relationship between Q_{50U} and mean annual peak

characteristics, should be found to have high correlation between the upper 50-year value and the lower 10-year value. This correlation between high and low values in the regimen of streams is necessarily associated with a fairly uniform coefficient of variation. To illustrate this uniform coefficient of variation in the author's sample it was convenient to plot his upper 50-year value against the mean value (furnished by courtesy of the U. S. Geological Survey) of the annual series for each of the 69 stations. Figure 7 shows this plot to have nearly as high correlation as the author shows for his relation of 10*L* to 50*U*, though the scatter is amplified by our having used linear paper.

The central tendency of the data in this diagram can be generalized by means of a line through the origin, and having a slope of 2.8. By multiplying the mean of the annual series by 2.8 the author's 50*U* values can be obtained more simply than by computing the 10*L* values first, and with comparable accuracy. Further, with a short record a better estimate can be made of the true mean value than of the true ten-year value.

The author has not shown that his upper 50-year values, defined by a least-squares line through the small number of points exceeding the five-year value, are superior to those obtained by any other method. We believe that the correlation between the upper 50-year and the lower ten-year values is not an adequate test of validity, but is a measure of the inherent consistency among the data in the author's sample.

Looking at this problem from a physical standpoint, a dichotomy of causes of annual peaks seems to be an over-simplification. The author has suggested several pairs of what we believe is a multiplicity of causes. This combination of many causes is one of the reasons for the statistical approach.

Manuel A. Benson (U. S. Geological Survey, Washington 25, D. C.; received May 8, 1958).—In the *Discussion* which closes his paper, the author disclaims any generality for the dog-leg shape of frequency curve or for the relations he has developed. This leaves unanswered the question of just how specific are the results which he has obtained. The sampling method and the area of applicability of the relations require explanation. The separation of a frequency curve into two distinct parts is also open to question.

It has been the experience of this writer that frequency curves of maximum annual peak discharges, when plotted on extreme-value probability paper, indicate a variety of shapes. Some are straight lines, most curve gradually either upward or downward, and relatively few appear to represent two straight lines.

The frequency curves for 96 records of annual peak discharge are shown plotted in Figure 8. These records, which have been reviewed and analyzed for publication in the series of compilation reports now being prepared for publication as U. S. Geological Survey Water-Supply Papers, represent all the long-term records available for stations with annual peaks not appreciably affected by regulation. They are generally over 45 years in length, with a median length of 53 years. They have been plotted together on a dimensionless basis by using as ordinate the ratio to the mean annual (2.33-year) flood; the shapes remain the same as though discharge were the ordinate. The curves have been drawn by eye, fitting the average trend of the plotted points as closely as possible. Most of these curves have a gradual curvature; only a very few can be interpreted as representing two straight lines. Potter's contention that the dog-leg shape "is especially noticeable when the period of record is 25 years or more" is not borne out by these curves.

Hazen [1930, pp. 102–105] speculated that the complex shape of frequency curves may be due to the multiple causes of floods. However, he concluded, "It is true of course that these causes grade into each other and that no lines of demarcation can be drawn." Potter's separation of high- and low-frequency curves at the five-year level is entirely arbitrary and does not actually separate peak discharges caused by different types of storms.

The separation of the frequency relation into two parts at the five-year level (each part made to fit a straight line) is not only arbitrary but is an oversimplification of the basic problem. Undoubtedly, this method is better than that which assumes a single straight line, yet not as accurate as one which might use say three straight lines or the curve which is the limit of n straight lines. The graphical method of fitting flood discharges is an approach towards expressing the underlying complex situation. It avoids the initial restrictions and perhaps the error of arbitrary assumptions. The range of error in the drawing of graphical curves may be smaller than that involved in assuming a fixed shape for the frequency relation.

Potter's method for finding a relation between the 10- and 50-year floods is as follows: (1) Plot the annual floods against recurrence interval on extreme-values probability paper. (2) Divide the data into two parts at the five-year point; compute a least-squares line for the upper points and fit a straight line to the lower points by eye. (3) Select values of Q_{10L}, Q_{10U}, and Q_{50} from these two lines. (4) Plot Q_{10L} versus Q_{10U} and Q_{10L} versus Q_{50} and compute least-squares lines for both. (The first line may always be expected to show good correlation, since it relates the equivalent of two adjacent points on the same frequency curve.) The second is the desired relation.

The following procedure is offered as an alternative: (1) Same as above. (2) Fit a curve to the data by eye. (3) Select Q_{10} and Q_{50} from this curve. (4) Plot Q_{10} versus Q_{50} and fit a curve by eye. This curve is the desired relation.

The writer applied this alternative procedure to Potter's data. Graphical frequency curves were used to determine Q_{10} and Q_{50} for the 69 stations in Potter's Table 1. Some of these curves (for Ohio, Iowa, Illinois, and North Carolina) were already available in published reports or in unpublished studies and were used without change. The rest were drawn independently of each other and, once drawn, remained unchanged. A plot was made of Q_{50} versus Q_{10}, as determined graphically from these curves. It was found that two-thirds of the points were included within 13 pct of the mean curve, as compared with 20 pct for the author's curve of Q_{50U} versus Q_{10L}. However, based on the discussion which follows, neither

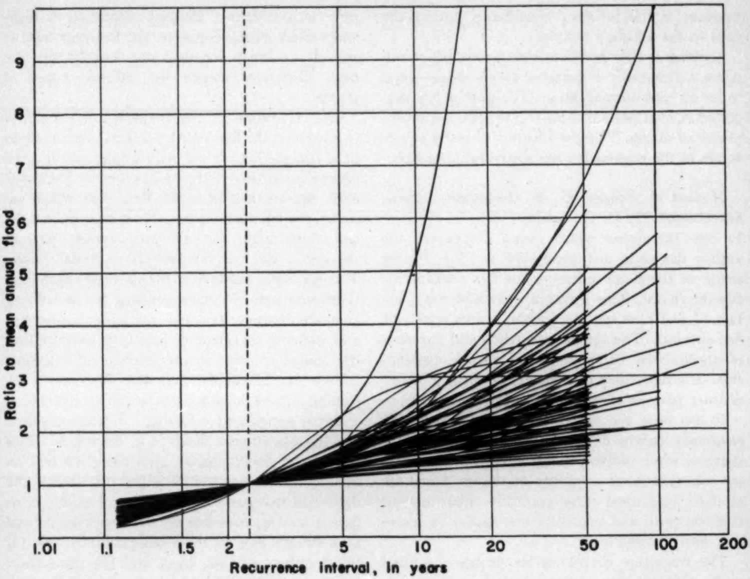

FIG. 8 – Frequency curves of annual peak discharge at long-term stations in the United States

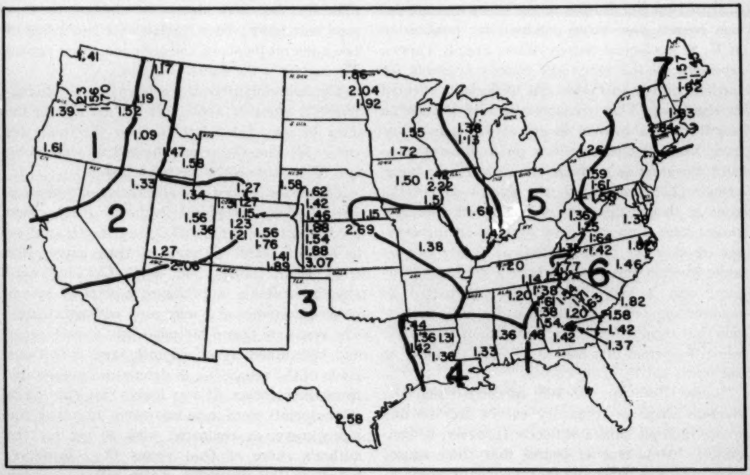
1
2
3
4
5
6
7
1.41
1.17
1.39
1.52
1.19
1.09
1.61
1.47
1.58
1.33
1.34
1.27
1.56
1.36
1.27
2.06
1.58
1.62
1.42
1.46
1.88
1.54
1.88
3.07
1.56
1.76
1.41
1.89
1.86
2.04
1.92
1.55
1.72
1.50
2.22
1.51
1.15
2.69
1.38
1.66
1.42
1.20
1.38
1.13
1.26
1.59
1.61
1.58
1.36
1.25
1.64
1.42
1.38
1.60
1.46
1.77
1.14
1.20
1.38
1.61
1.38
1.54
1.20
1.58
1.42
1.42
1.37
1.82
1.44
1.36
1.31
1.42
1.36
1.33
1.36
1.46
1.57
1.62
1.83
2.58

FIG. 9 – Ratio of 50-year to 10-year flood, with subdivision into regions

this relation nor Potter's corresponding relation is considered significant.

Potter used the "sample of 69 gaged watersheds" to develop a relation of Q_{50} to Q_{10}. However, the area where this relation applies is not specified. Does it apply to the entire United States? Perhaps it applies to the Piedmont Plateau, to the West Slope of the Rocky Mountains, and to the States of Missouri, Ohio, Iowa, Illinois, and New York, because data from each of these areas have been used. If so, why are some areas represented by many stations, whereas the States of New York and Wisconsin are represented by only one station each? The writer would be interested in the method of sampling used, as the basis for selection is neither stated nor implied. When only a portion of the available data is being used, an unbiased and clearly defined sampling method is required to give meaningful results. If the developed relations apply only to selected points which happen to plot together, they have little significance.

Note that the author's curve of the relationship of Q_{50U} to Q_{10L} is a straight line on log paper at virtually a 45° angle (the slope was tested by the writer and proved not to be significantly different from 1.0). This line is equivalent to a constant ratio of 1.65 for the 50- to 10-year peak.

To investigate the variability of the Q_{50} to Q_{10} ratio for the entire United States, the writer made an independent study using the 96 long-record stations whose frequency curves are shown in Figure 8. The locations of these stations and the Q_{50}/Q_{10} ratios, determined from individual frequency curves, are shown on the map of Figure 9.

Statistical techniques are available for investigating whether a general average (of the Q_{50} to Q_{10} ratio) might be suitable for the entire United States. If the data can be grouped in some logical manner, tests can indicate whether the groups are from the same basic population. The country was divided into seven parts; the boundaries were chosen so as to separate regions of high and low ratios, as indicated by the data.

A standard analysis of variance computation was first made. The standard F test [*Snedecor*, 1946, pp. 231–233] shows the variance between regions to be very significantly larger than the variance within regions. This method assumes normal distribution of the data, an assumption which is not necessarily true of hydrologic data. A nonparametric test, the Kruskal-Wallis one-way test of analysis of variance by ranks [*Siegel*, 1956, pp. 184–199; *Wallis* and *Roberts*, 1956, pp. 599–601] was therefore made in addition. This test confirmed the result of the standard F test.

This study indicates that there are highly significant differences in the 50- to 10-year ratios which remain to be examined and, if possible, explained. The regions as outlined in Figure 9 are not necessarily the best way of subdividing the country. The picture will no doubt be changed as more long-term records become available. The means and medians of the separate groups indicate that possibly some of the seven groups might be combined. However, the groups which represent the extremes should not be considered together; for example, groups 2 and 5, having low ratios, and groups 3, 6, and 7, having high ratios, should not be considered as part of the same population.

The author's method has been proposed as a means of using short-term records to predict 50-year floods. Well-established methods are available for using short-term records together with long-term records in developing regional flood-frequency relations. These regional methods reduce the chance error inherent in individual records, particularly short records, and furnish estimates of not only the 50-year flood but of floods of any recurrence interval within the time range of the longer records, at either gaged or ungaged points.

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WALLIS, W. A., AND H. V. ROBERTS, *Statistics, a new approach*, Free Press, Glencoe, Ill., 646 pp., 1956.

R. Robinson Rowe (California Division of Highways, Sacramento, Calif.; received June 17, 1958) —All techniques refining observations of extreme floods on a frequency basis add to our knowledge, by induction, of the real laws of nature. The addition may be in the form of new hypotheses or support for the old. Potter's paper contains both elements.

His end result appears to be the two unnumbered equations on page 101, the difference of which is

$$\log Q_{50U} - \log Q_{10U} = 0.166 + 0.001 \log Q_{10L}$$

Since the last term never exceeds 0.002 for his data, it may be ignored to find

$$Q_{50U} = AQ_{10U} \quad \text{where} \quad A = e^{0.166} = 1.47$$

TABLE 2 – *Group summary of basic data*

Group	Items	Values of A		
		Min.	Mean	Max.
Iowa	9	1.30	1.62	1.88
Piedmont	21	1.21	1.54	1.86
Missouri	12	1.26	1.51	1.77
Western	8	1.26	1.47	1.71
Ohio	10	1.22	1.39	1.67
Illinois	7	1.17	1.38	1.65
Miscellaneous	2	...	...	...
Total	69	1.17	1.50	1.88

If we now examine the ratio A of Q_{50U} to Q_{10U} for the 69 streams of his Table 1, by groups, we find (Table 2) strong indications of heterogeneity. The groups have been rearranged in order of mean value of A, which ranges from 1.62 in Iowa to 1.38 in Illinois. With one exception, the maximum and minimum values of A follow the same order, indicating similar dispersion of the basic data.

If the several groups are all part of a homogeneous region the conformance would be accidental and A would be constant near 1.50 (the mean) or 1.47 (as derived above). The dispersion (1.17 to 1.88) would be a measure of error due to short records, expressed by quartiles as 1.50 ± 0.16.

On the other hand, if the conformance is systematic, the region may be a heterogeneous collection of relatively homogeneous sub-regions for which A ranges from 1.38 to 1.62 but is nearly uniform in each group. For the largest group, the quartile measure of error would be expressed as 1.54 ± 0.13. The writer prefers this interpretation even though the adjoining regions of Iowa and Illinois differ the most.

The ratio A for two California regions can be scaled from another study of this problem [*Rowe* and others, 1957], finding $A = 1.58$ in northwestern California (Fig. 4) and $A = 1.98$ in the Sierra Nevada Mountains (Fig. 5). Station records would have ranged from 1.2 to 2.8. Hence the two studies agree in principle that the ratio A is an important hydrologic factor for a watershed which is constant (within a moderate range) for a homogeneous region, and that this constant is approximately determinable by combination of poorly-defined short-period station records.

Both studies also call attention to and dispose of the characteristic dog-leg form of frequency curves. Agreeing that the shape is caused by sampling from two different populations, the author presumes enough correlation between the populations to define empirical relations. The writer prefers the referenced California study which discards the minor population, apparently distinguished by its plotting along the lower limb of the dog leg.

To support the diagnosis that dog-leg frequency curves derive from mixed samples, the author presented Fig. 6 to show a clean sample from a melt stream with a fairly straight curve. Although he described it as having "no dog leg at all," a better fit can be obtained with a slight dog leg. Replotting to include the 1956 flood (1680 cfs), the dog leg is substantiated with the following values

$$Q_{2L} = 0.74, \quad Q_{10L} = 1.09, \quad Q_{10U} = 1.16,$$

$$Q_{50U} = 2.05 \quad A = 1.77.$$

So, while this stream (Bear Creek near Lake Thomas A. Edison) is usually a melt stream, its record of peaks is a mixed sample. All but the two largest were melt floods in May and June. The other two were due to heavy rain on a snow cover, July 21, 1936, and July 26, 1956.

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ROWE, R. ROBINSON, GORDON L. LONG, AND THOMAS C. ROYCE, Flood frequency by regional synthesis, *Trans. Amer. Geophys. Union*, **38**, 879–884, 1957.

W. D. Potter (Bureau of Public Roads, Washington, D. C.; Author's closure)—I wish to thank the discussers for their interesting comments. Since writing the paper, I have had the occasion to establish the relations between Q_{10L} and Q_{50U} for three physiographic areas; namely, (1) the Adirondack, White Mountains, and Maine Woods area, (2) the New England Hill and Lowland area, and (3) the Southern Rocky Mountains area. It was found that, by establishing these relations for individual physiographic areas, the spread of the error bands for 68 pct of sample was reduced from one-half to one-fourth of the ±20 pct found for the sample used in the paper. The relations between Q_{10L} and Q_{10U} and between Q_{10L} and Q_{50U} were used in analyzing peak rates of runoff for each of the above physiographic areas.

Reviews, Abstracts, and Bibliography

Reviews and Abstracts

GEORG WÜST, *Wissenschaftliche Ergebnisse der Deutschen Atlantischen Expedition auf dem Forschungs- und Vermessungsschiff-Meteor, 1925–1927*, vol 6, part 2 section 6, Stromgeschwindigkeiten und Strommengen in den Tiefen des Atlantischen Ozeans, pp. 261–420, Walter de Gruyter and Co., Berlin, 1957.

It is with a feeling of reverence that I take up the task of reviewing Dr. Georg Wüst's most recent contribution to the long and distinguished series of volumes of reports of the German *Meteor* Expedition (to the South Atlantic Ocean) of 1925–1927. For over thirty years now the reports of the *Meteor* Expedition have set the highest standard for publication of the results of oceanographic investigation: complete documentation of the actual original data obtained, the methods of observation, definitive and handsome atlases and complete and explanative studies and interpretation of the meaning of the results. Since the time of the *Meteor* Expedition, much oceanographic survey work has been done, but never in quite the same systematic way, nor have the results of any of the later expeditions been written up in such a thorough fashion: indeed the *Meteor* work has been the model after which the recent IGY surveys of the Atlantic have been made. Wüst has long been recognized as the world's leading authority on the deep circulation of the ocean, not only in the South Atlantic, but in the oceans of all the world. There is no one who has immersed himself more deeply in the study of hydrographic observations, and no one else has contributed so much toward developing a comprehensive picture of the circulation of the world ocean as a whole. Because this is Wüst's last contribution to the *Meteor* reports, and in view of his imminent retirement as Director of the *Institut für Meereskunde der Universität Kiel*, it is appropriate to express here, in this review, the admiration and gratitude of the world's oceanographic fraternity for the legacy and fruits of his wisdom and industry. And we can hope that in his retirement he will be able to favor us, from time to time, with the products of his deep understanding of the ocean.

In the first three chapters Wüst presents a complete compilation in tables, graphs, and profiles of the vertical distribution of specific volume and dynamic depths for all the *Meteor* data. Using the level of no motion proposed by *Defant* [1941], Wüst proceeds, in Chapter 4, to present complete profiles with contour of constant geostrophic velocity. In Chapter 5 the amount of mass transport between each pair of stations and between standard depths is also presented. Finally, in Chapter 6, computations of the transport of salt and of dissolved oxygen are presented. All these computations are reproduced in complete detail so that the reader can have no difficulty reconstructing all portions of the argument.

During recent years [*Iselin*, 1955] there has been growing concern over the accuracy and limitations of geostrophically computed currents. Occasionally, in councils of despair, it has been suggested that the method is hopelessly inaccurate and that the mean circulation is dominated by gross turbulent viscosity. Wüst has made use of an intuitively chosen reference level (of no motion) originally proposed by *Defant* [1941] on purely intuitive grounds (a possible physical basis is given by *Stommel* [1958, p. 158]). The results of the computation for transport through the *Meteor* profiles are summarized in Tables 12 and 13; pages 368 and 370 are quite remarkable for the high degree to which a balance between flows northward and southward is achieved. Does this mean that the geostrophic method is vindicated as good beyond all expectations?

First, of course, it is no surprise that the Defant reference level should be a first approximation of the truth: it would probably not have been used by Wüst if it had not already passed a preliminary test by Defant with the *Meteor* data.

Second, the very large transports ΣW that appear in Table 12 are largely made up of rather small scale pairs of nearly balancing currents and countercurrents occurring between successive stations (these can be seen in extreme form in the isotach profile II on page 330). As Wüst explains (p. 369), were a profile to contain more stations, one would expect more current-countercurrent, and hence the individual ΣW_+ and ΣW_- values to increase, but the balance to remain unaffected. Wüst does not claim that these pairs of currents in mid-ocean (above and below the arbitrary reference level) are all permanent oceanic features; the fact that such a careful author does not lay more stress upon them suggests that he prefers not to interpret them as bona fide current systems, but leaves the possibility open that some may actually be due to momentary disturbances of the density field of a short duration. Such ambiguities are part of the reason why other oceanographers have been so uncomfortable about the geostrophic approximation. When transports per unit depth are computed for the full width of an ocean basin, or for the whole western or eastern trough, the contribution of these ambiguities is minimized, as Wüst shows, and one is bound to agree with the author that these integrated transports compare most beautifully with the expectations of water mass analysis (the intermediate water excepted) each computed current maximum coinciding nicely with the center of a particular water type.

A good balance is also obtained for salt-transport (integration over a whole profile of the product of mass transport and salinity) but as Wüst points out this result is really quite insensitive to the actual salinity distribution in the profile. In fact, he shows that much the same result can be obtained by multiplying the net mass transport for the profile by the mean salinity. Thus the salt-transport computation does not serve as an independent check on the consistency of the Defant reference level and geostrophic approximation. This shows that an attempt to work backwards from the principle of conservation of mass and salt, and thus to determine the reference level, is in fact impossible (although it seems to work for small straits and estuaries [*Sverdrup* and others, 1942, p. 426, 457]).

One of the main results of Wüst's study is the amazing concentration of deep currents in limited, narrow, high velocity western boundary currents often lying right on the continental slope of South America. The existence of these currents has an important bearing on theoretical studies of the deep circulation [*Stommel*, 1958, pp. 157–172]. Profile VI (p. 333) shows them in beautifully developed form although they are not so clear on other profiles for example, Profile II, p. 330). So narrow that they often fall between two stations, with computed velocities of as much as 17 cm/sec, they carry a large fraction of the total meridional transport of water, the remaining immense water masses to the east being relatively slow moving. Were a particle able to remain inside so swift a stream, and were the stream itself a continuous ribbon, only a few years would suffice to carry it from the South Atlantic. This rapid motion should not be confused with the turn-over time (residence time or age) of deep water because most of the deep water does not move so swiftly, and is presumably in active exchange by lateral mixing processes with these western boundary currents. This reviewer thinks that our hypothetical particle could not stay in a western boundary current for long, but would quickly be transported out into the slower moving immense water masses in the middle of the ocean; that much of the turbulent exchange from the western boundary current is by lateral mixing with the interior, rather than by vertical mixing; and that therefore Wüst's tabulation of vertical Austausch only (p. 343, Table 3, Col. 11) is somewhat misleading and that the real values are much lower. My reason for feeling that there must be a relatively large lateral exchange of salinity, temperature, and dissolved oxygen between the western boundary current and the interior is that their water-mass properties are so similar despite the fact that their velocities and transports are so different. In the absence of any marked interchange one might expect a very marked contrast in water-mass properties, particularly oxygen, between them. Indeed it was this very lack of contrast which earlier led oceanographers to think of the deep circulation as a broad sluggish meridional transport fairly uniformly distributed over the entire width of an ocean basin.

Other reasons for supposing that the western boundary currents are not perfectly defined steady ribbons of flow are that from profile to successive profile there is a marked variability in the strength of the current (for example, see Table 28, p. 347), and that the profiles of the *Crawford* (1957) along 8°S and 16°S, seem to show details in the western boundary current region that are different from those in the corresponding *Meteor* profiles (VIII and VI). Over most of the deep water, however, according to Fuglister, the recent *Crawford* sections show virtually no difference from those of the *Meteor* some 30 years ago, thus verifying, in a most convincing manner, the assumption by Wüst that the deep circulation is in a climatologically mean steady state.

In retrospect it seems that Wüst, by means of this latest addition to the *Meteor* series, has been able to bring his whole concept of the circulation of the Atlantic into sharper focus, and that there can hardly be any doubt that he has been able to delineate the main features of this great natural phenomenon. By providing us with the rich detail of the complete dynamical calculations of the *Meteor* data he has given us a ready source of material for thinking about the strengths and weaknesses of the geostrophic approximation. And by his personal example of rigorous and meticulous adherence to the data itself and his thorough study of it, without frills, and with a minimum of speculation, Wüst will influence many oceanographers in the years to come. Let us applaud him.

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HENRY STOMMEL

HELMUT WEICKMANN AND WALDO SMITH, editors, *Artificial Stimulation of Rain*, 1957, Pergamon Press, 427 pp., $15.00

This book is a printed record of the Proceedings of the First Conference on the Physics of Clouds and Precipitation Particles which convened at Woods Hole, Massachusetts, September 7–10, 1955. Organized under the impetus of the Committee on Cloud Physics of the American Geophysical Union, the meeting was sponsored by the Geophysics Research Directorate of the Air Force Cambridge Research Center and the Geophysics Branch of the Office of Naval Research with the cooperative assistance of the Woods Hole Oceanographic Institution.

This book is a useful reference volume for anyone interested in the study of the physics of natural clouds and precipitation. It is divided into several parts according to subject matter as follows: (1) Aerosols; their origin, distribution, and measurement; (2) Condensation and coagulation; measurement of cloud- and rain-drop size, rain from water clouds; (3) Melting and freezing; studies of snow and ice in the generation of precipitation; and (4) Crystal growth and nucleation; laboratory and field studies. In addition there are two papers, one on thunderstorm electricity and another on 'International Terminology,' which are not included in the previous four classifications.

The initial value of the conference in gathering together the leaders in research in these fields for discussions is considerably augmented by the publication of this permanent reference volume. However, the conference was not called to discuss "The Artificial Stimulation of Rain" and indeed such a title would have been considered unfortunate at the time when New England was still staggering from the floods which had occurred only three weeks previously. Unfortunately, in the final rush to get the book into print, the editors did not have an opportunity to approve the final title selection.

However, for those who buy the book on the basis of its title there are to be found therein (1) the results of using common salt for cloud-seeding experiments in Pakistan, and (2) a study of the overseeding of cumulus clouds. Needless to say, however, the basic research discussed is a necessary forerunner to the complete understanding of physical cloud processes which may lead to successful future control of such processes by man. Among the many interesting topics are some discussions of Bowen's controversial hypothesis on the meteoritic origin of world-wide rainfall singularities by Christian E. Junge and Vincent J. Schaeffer plus the results of an experiment to test Bowen's hypothesis by means of daily freezing nuclei counts. The latter paper is by A. Richard Kassander, Lee L. Sims, and James E. McDonald.

The reader will also be pleased to note the various techniques which have been used by the authors to explore clouds from within by various sampling processes and by radar.

Each paper is followed by an apparently verbatim account of the lively discussions which took place. A pleasing note is the inclusion of a frontispiece consisting of a photograph of the conference participants.

Conrad P. Mook

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Notes and Personalia

Notes

Corrigendum—In the paper by S. Irmay in the August 1958, issue of the *Transactions*, page 705, the last line, Eq. (34) should read

$$J/[(a/2) + \sqrt{(a^2/4) + Jb}] = Jf(J)$$

instead of as shown, the radical having been omitted in the left-hand member.

National Science Foundation Graduate and Postdoctoral Fellowships for 1959–1960—The National Academy of Sciences - National Research Council will again assist the National Science Foundation in its eighth regular predoctoral and postdoctoral fellowship programs. There is the plan to award about 1000 graduate and 200 postdoctoral fellowships under these programs for the next academic year. Fellowships are open to all citizens of the United States and are awarded solely on the basis of ability in mathematical, physical, medical, biological, and engineering sciences. The closing date for the postdoctoral fellowships is December 22, 1958, and for the predoctoral fellowships, January 5, 1959. Inquiries should be addressed to the Fellowship Office, National Academy of Sciences - National Research Council, 2101 Constitution Avenue, N. W., Washington 25, D. C.

Structural Research Program in Seismology—California Institute of Technology has announced the installation of 100 small, inexpensive seismographs in Los Angeles and San Francisco in an effort to determine the characteristics by which soils absorb earthquake shocks and which soils are better than others. This is of especial concern in building and bridge construction. The study is under the direction of George W. Housner, Professor of Civil Engineering and Applied Mechanics at the Institute.

New Examination for Geodesists—The Civil Service Commission has recently announced (Announcement No. 168 B) an examination with no closing date for geodesists at salaries ranging from $4,040 to $12,770 per year in grades ranging from GS-5 to GS-15. For details get in touch with one of the offices of the U. S. Civil Service Commission.

Grant for High Energy Nuclear Particle Research in Balloons—The National Science Foundation has made a grant of $450,000 to the University of Chicago for work with a group of scientists under Marcel Schein for the study of tiny nuclear explosions with energies on the order of ten thousand billion electron volts by means of balloon flights to altitudes of 120,000 ft.

New Publication in Meteorology—A new publication entitled Nubila is now being published quarterly by the Unione Nazionale Antigrandine, Via Pellicciai, 17, Verona, Italy. The Editorial Committee consists of G. Fea, F. H. Ludlam, E. Rosini, P. M. Saunders, and O. Vittori, with Ovidio Romanelli as Director. The first number is devoted to the hail problem, a paper by F. H. Ludlam.

New Publication in Geology—The Universidad Industrial de Santander has released Number 1 of its *Boletín de Geología*. The first number contains two papers, one entitled "La Morfoestructura de la Zona de Mesas al SW de Bucaramanga," by M. Julivert, and the other entitled "Observaciones sobre la variabilidad de las especies," by J. de Porta. Interested persons should address the Fondo Rotatorio de la Universidad Industrial de Santander, Apartado Nacional 162, Aéreo 678, Bucaramanga, Colombia, S. A.

Geothermal Power Plant Opened in New Zealand—New Zealand has recently started operation of its first geothermal steam power plant at Wairakei, 60 miles south of Rotorua on the North Island, with a capacity of about 250,000 kilowatts. Explorations are being made for further development in other nearby areas which may be even more favorable for the production of power.

New Edition of the *American Practical Navigator*—This book, commonly known as "Bowditch," after Nathaniel Bowditch, author of the first edition, has been completely revised by the U. S. Navy Hydrographic Office. The new 1524-page edition became available December 6, 1958, from the Superintendent of Documents, Washington 25, D. C., at a price of $6.25.

Bathyscaphe Acquired by the U. S. Navy—The bathyscaphe *Trieste*, launched by Auguste and Jacques Piccard in 1953, and which was rented for research dives off Capri in the Mediterranean, was recently purchased by the U. S. Navy.

New Volcano in Ruanda-Urundi—Word has come that early in August a new volcano developed in the extensive equatorial rain forest in the eastern part of the Belgian Congo about 35 miles north of Lake Kivu. The cone was estimated to be about 400 ft high and a quarter of a mile in diameter early in September, with lava flows as long as 15 miles. It has been named Kitsimbanyi, which means 'high and strong.'

Russian Studies of Glacier Thickness and Structure—The Zailiyskiy Glacier Expedition of the Academy of Sciences, USSR, is making a study of the thickness and structure of the Tuykus Glacier using electrical and magnetic methods which are indicated to be much less cumbersome and expensive for such purposes than the seismic method.

Second Caribbean Geological Conference—This Conference is to be held at the University of Puerto Rico, Mayaguez, Puerto Rico, January 5–9, 1959, by arrangements with the University of Puerto Rico in cooperation with the Economic Development Administration of the Commonwealth of Puerto Rico. Sessions will be held on general problems of Antillean structure, geology of various parts of the Caribbean, economic geology, and other subjects and will be joined with several field trips. Accommodations, however, are quite limited. Communications regarding this should be addressed to John D. Weaver, who is Chairman of the Committee on Arrangements, Section of Geology, College of Agriculture and Mechanic Arts, University of Puerto Rico, Mayaguez, Puerto Rico.

Course on the Biology of Stream Sanitation in Munich—Word has come from the Bayerische Biologische Versuchsanstalt of an introductory course on the Biology of Sewage and Stream Sanitation to be held March 2-6, 1959, under the direction of R. Demoll and H. Liebmann of the Research Institute. This will be followed October 5-10, 1959, by an advanced course on "Possibilities and Limits in Removing Poison and Radioactive Substances from Sewage and Industrial Waste Waters." The registration fee for each of the courses is DM 60, including traveling expenses on excursions. Interested persons should get into touch with Prof. Dr. H. Liebmann, Bayerische Biologische Versuchsanstalt, Veterinärstrasse 13, Munich 22, Germany.

Meeting on Agricultural Meteorology of WMO—The Commission for Agricultural Meteorology of the World Meteorological Organization held a three-week meeting in Warsaw, Poland, closing on October 17, 1958. Representatives from 32 countries were present. The meeting dealt with the various aspects of meteorology of interest for agriculture and forestry, including weather forecasting for forest-fire prevention and frost warnings. The session was presided over by J. Burgos of Argentina, and near the end of its meeting elected Austin Bourke (Assistant Director for Research and Development, Meteorological Service, Dublin, Ireland) as President and M. S. Kulik (scientist of the Central Forecasting Institute of the Hydrometeorological Service of the USSR) as Vice President. Attending from the United States were William E. Hiatt and Milton L. Blanc.

Conference on the Arid Zone—Arid Zone Research has become a major project of UNESCO and held its fourteenth session at Teheran, October 7-9 and 19, 1958. Reports of the activities since the last meeting in 1957 were presented. Details may be secured by writing to the UNESCO office in Paris. Attending from the United States was C. W. Thornthwaite.

Personalia

S. Joshua Buckwold has resigned his duties as Assistant Professor of Chemistry at New Mexico Institute of Mining and Technology to accept an Associate Professorship at the College of St. Joseph in Albuquerque, New Mexico.

Bernard Haurwitz, Chairman of the Department of Meteorology and Oceanography of New York University, has accepted a position as Professor of Astrogeophysics at the University of Colorado and a member of the staff of the High Altitude Observatory. He will take up his new duties in June 1959.

Weikko A. Heiskanen, Director of the Geodetic Institute of Helsinki, Finland, and of the Institute of Geodesy, Photogrammetry and Cartography of Ohio State University, has recently been awarded an honorary degree of Doctor of Technology by the Finland Institute of Technology on the occasion of the Fiftieth Anniversary of the Institute.

Koji Hidaka, Professor at the Geophysical Institute of Tokyo University, has been elected a member of the Pacific Science Council to take the place of A. P. Elkin of Australia.

W. T. Holser has left his work at the Institute of Geophysics, University of California, to take up a research position in the Geology Division of the California Research Corporation at La Habra Laboratory.

Benjamin G. Holzman, Colonel in the U. S. Air Force, has been made Commander of the Air Force Office of Scientific Research with headquarters in Washington, D. C.

Arno T. Lenz has been appointed Head of the Department of Civil Engineering at the University of Wisconsin. He has been a member of the University staff since 1929.

Gösta H. Liljequist has been designated as Director of the Department of Experimental and Theoretical Meteorology of the Meteorological Institution at the Royal University of Uppsala, Sweden.

Morton J. Rubin, U. S. Weather Bureau meteorologist stationed with the Soviet IGY Antarctic Expedition at Mirny, reports a new world's record low temperature observed at Sovetskaya (78°24'S., 87°35'E.) on June 25, 1958, when the temperature fell to −117.4°F or −83.0°C. Details of this observation are published in the Monthly Weather Review for June 1958. A later report published in Moscow in vodnyy Transport for August 19, 1958 states that V. Babarykin, chief of the Sovetskaya station, registered a temperature of −86.7°C on August 9, 1958.

R. D. Russell, formerly an Assistant Professor at the University of Toronto, has been appointed Associate Professor of Geophysics at the University of British Columbia.

Arthur H. Waynick, Professor and Head of the Department of Electrical Engineering and Director of the Ionosphere Research Laboratory at Pennsylvania State University, has been appointed Program Director for Engineering Sciences of the National Science Foundation.

Wesley Winans Horner, Consulting Engineer of St. Louis, died September 22, 1958, at the age of 75. He was born at Columbia, Missouri, and took his baccalaureate degree from Washington University in 1905. This school awarded him a professional degree in 1909 and an honorary degree of Doctor of Engineering in 1952. His early career was devoted to engineering in the service of the city of St. Louis, becoming Chief Engineer in 1932. He opened a consulting practice in 1916, to which he devoted full time from 1932 onward, organizing the firm of Horner and Shifrin in 1933. During this interval he served his alma mater as Lecturer and Professor of Sanitary Engineering from 1934 to 1942, and served the Federal government as a consultant in various ways. He had been a member of the AGU since 1938.

Pierre Lejay, well-known Jesuit scientist, died October 11 at the age of 61, on shipboard en route to his home in Paris following his attendance at the General Assembly of the International Council of Scientific Unions in Washington, D. C. He was Vice President of ICSU, had been active in the International Union of Geodesy and Geophysics for many years, and was currently Chairman of the French National Committee for the IGY.

Union, Section, and Committee Activities

Minutes of Executive Committee Meeting, American Geophysical Union, October 18, 1958

The meeting was called to order at 09h 00m in the Tayloe-Cameron Rooms of the Cosmos Club, 2121 Massachusetts Ave., N.W., Washington, D. C., by Vice President Lloyd V. Berkner, who reported that President Maurice Ewing had been delayed and that routine matters would be taken up until he arrived.

Present—P. H. Abelson, L. H. Adams, L. T. Aldrich, L. R. Alldredge, W. W. Atwood, Jr., Lloyd V. Berkner, Walter H. Bucher, J. J. Capello, Maurice Ewing, Robert E. Gebhardt, W. C. Hendrix, Harry H. Hess, Albert J Hoskinson, Floyd W. Hough, B. F. Howell, Jr., Patrick M. Hurley, Woodrow C. Jacobs, J. W. Joyce, H. E. Landsberg, Walter B. Langbein, L. M. Murphy, J. H. Nelson, James A. Peoples, Jr., Charles Pierce, D. W. Pritchard, John C. Reed, A. Nelson Sayre, J. Frank Schairer, Waldo E. Smith, Charles A. Whitten, and Ralph N. Wilson.

Approval of minutes—The minutes of the Executive Committee meeting held on May 4 and 7, 1958, and published in the August 1958 issue of the *Transactions* (pp. 755-766), were approved.

General Secretary's Report

The last report of the General Secretary is recorded in the minutes of the Executive Committee meeting of May 4 and 7, 1958, published in the August 1958 issue of the *Transactions* (pp. 755-758). Since that time the following changes in our Executive Committee have taken place: H. Burr Steinbach of the University of Chicago has succeeded L. A. Maynard as Chairman of the Division of Biology and Agriculture of the NAS-NRC, Ernest H. Volwiler of Abbott Laboratories has succeeded Frederick D. Rossini as Chairman of the Division of Chemistry and Chemical Technology of the NAS-NRC, and John N. Adkins has succeeded Harry H. Hess as Chairman of the Division of Earth Sciences of the NAS-NRC.

Actions of Executive Committee by mail ballot—Since the last meeting of the Executive Committee there have been 13 actions by the Committee by mail ballot as follows:

Date	Subject	Approve	Disapprove
1958			
May 20	Corporation Members: W. F. Sprengnether Instrument Co., Radio Corporation of America, International Business Machines	41	0
June 2	Corporation Members: General Dynamics Corp., Bell Telephone Laboratories, Union Carbide Corp., Stanford Research Institute	41	0
June 27	Fourth list of new members	40	0
June 30	Corporation Member: Geophysical Associates International	40	0
July 2	Provisional Budget for fiscal year 1959	33	2
July 3	Corporation Member: International Telephone and Telegraph Corp.	38	0
July 9	Changes of rules for elections	37	0
July 9	Corporation Member: Standard Oil Co. of New Jersey	37	0
July 16	Corporation Member: Ramo-Wooldridge Corp.	37	0
Aug. 12	Approval of co-editors for *JGR*	36	2
Aug. 19	Fifth list of new members	39	0
Sep. 19	Sixth list of new members	38	0
Sep. 24	Corporation Member: Motorola, Inc.	38	0

In addition, one more ballot is pending at this time relating to the seventh list of new members for 1958.

It should also be reported that the ballot to the membership on the changes in the Statutes was overwhelmingly in favor of the change by about 28 to 1 according to the Tellers' report which will be presented later. Over 2200 votes were cast. Although we are still awaiting word of a grant from the National Science Foundation to aid us to expand the content of our new scientific journal, the officers have been proceeding on faith that this matter will be taken care of in due course, and plans are developing rapidly to issue the new journal promptly in January 1959.

Publications—The following issues of the *Transactions* have been printed and distributed since our last meeting:

June 1958	230 numbered pages of text plus 18 unnumbered pages including 8½ pages of paid advertising; edition of 6400
August 1958	192 numbered pages of text plus 16 unnumbered pages including 9 pages of paid advertising; edition of 6400

The October 1958 issue is in the final stages of publication in the hands of the printer, and will contain 220 numbered pages of text plus 20 unnumbered pages including 9 pages of paid advertising, with an edition of 6400. Immediately inside the front cover of the October issue we plan to publish a four-page promotional leaflet relating to the publication policy. The first page of this will be the front cover of the new journal, and the second page will be essentially the inside front cover insofar as it can be prepared at this time. The third page will be devoted to an outline of the endeavor both with regard to the new monthly journal and the new quarterly *Transactions*, while the fourth page will contain a list of forthcoming papers in the new monthly journal.

We have continued to publish the *IGY Bulletin* in each issue of the *Transactions*. Aside from the *Bulletin*, the number of printed pages has been somewhat larger than we had anticipated because we want to reduce the backlog of papers on hand to a minimum so that the editors of the new journal would have a free hand to develop the journal in accordance with proposed plans. This increase in the number of regular text pages, plus the increase in printing costs, is causing a substantial deficit. An application for a grant of $15,000 to cover this deficit has been submitted to the National Science Foundation. No formal word has as yet been forthcoming, but informal word is that late in October we will receive a grant covering this.

Advertising in the *Transactions* has continued about nine pages an issue. Our advertising representative is faced with a difficult task in selling more advertising at this time because the format and content of the new journal are still in the planning stages. There is some thought also that even though we believe that the chief advertising medium should be our new journal, we might also carry advertising (if advertisers so desire) in the new quarterly *Transactions*, perhaps offering a combined rate to those who advertise in both. The basic rate for advertising in the new journal will be $250 per page, offering a 6-number contract for the price of five and a 12-number or one-year contract for the price of nine. The same basic rate will apply to the quarterly *Transactions*, namely, $250 per page, with a 4-number contract at the price of three. A combined contract for both the *JGR* and the *Transactions* would be 16 numbers for the price of 11. This would apply only to advertisers taking a full year's advertising in both publications.

The Editorial and Publication Committee has met regularly at bimonthly intervals to consider the many problems of the *Transactions*, as well as to cooperate in the development of plans for the new journal. It plans to have its last meeting on November 20. All of the current editors have been invited to serve as associate editors on the new journal. A total list of about 30 associate editors, including foreign associates, is being established, one-third of whom will retire at the end of each year.

With regard to plans for the new journal, the Executive Committee has approved by mail ballot the appointment of Philip H. Abelson and James A. Peoples, Jr., who will serve as co-editors in chief, with the editorial office of the Union for the journal being established with Peoples, ℅ Department of Geology, University of Kansas, Lawrence, Kansas. Mrs. Peoples is being designated as an editorial assistant to take care of the mechanics of editing and to handle a great deal of the detail relating to the publication of the journal. It is anticipated, however, that the proofreading of the journal will be undertaken in the office of AGU.

Geophysical Monograph No. 2 entitled *Geophysics and the IGY* was published in July 1958 about five weeks after the receipt of the last copy from authors. Twelve hundred and thirty copies have been sold to date, and, after supplying certain review copies (24) and one to each author (34), we now have on hand 1043 copies for sale. The total edition was 2331. We still have on hand 405 copies of Geophysical Monograph No. 1.

An application for a grant of $3800 has been made to the National Science Foundation to enable us to proceed with Geophysical Monograph No. 3, which would contain papers presented at the Conference on Atmospheric Chemistry of the Compounds of Chlorine and Sulphur held in Cincinnati, November 4–6, 1957, under the joint sponsorship of the Public Health Service and the AGU with the support of a grant from the National Science Foundation. This application has been pending since March 20, 1958, and we have informal word that it has been approved.

We plan to file an application for a grant for the underwriting of a number of monographs, say, three to five a year, over the next several years. The National Science Foundation has requested that a Monograph Board be established prior to the filing of this application and that information on contemplated numbers of this series be supplied in the grant application. These matters are pending.

The Russian translation project is still moving slowly. Pergamon Press has now delivered the first five numbers of *Izvestiia* (Geophysics Series) for 1957, and a single copy of No. 7 arrived October 14 of which no quality evaluation has yet been made, leaving six still to be published. The quality of the translations is somewhat improved from the earlier two numbers. Nos. 6 and 8 are reported to be nearly finished. Members of the Board and others have reviewed the typescripts of the translations for Nos. 9 to 12, inclusive. This will doubtless improve the quality of the translations substantially. A supplementary grant to provide for the completion of this is momentarily expected from the National Science Foundation. We have applied to the National Science Foundation for continuation of the translation of *Izvestiia* for 1958, and we understand that the funds will be forthcoming within the next few weeks. The method of procedure has not yet been settled. However, the proposal to carry on the project by translators selected by AGU has received considerable support. This would involve establishment of a system similar to the one used by the American Institute of Physics for the *Journal of Experimental and Theoretical Physics* with a translation editor, a panel of translators, and arrangements with a lithographic concern to set up (we might undertake the composition ourselves in the way that we formerly handled the *Transactions*), print, and distribute the English edition of the journal. We also have applied to the National Science Foundation for a grant to translate and publish an English edition of *Trudy* of the Geophysical Institute of the USSR for 1958.

The project for the translation of abstracts has been formally terminated, and the balance on the grant has been returned to the National Science Foundation.

Membership—Membership data as of October 6, 1958, are:

Membership as of April 21, 1958	5008	
(This figure included 148 tentatively dropped, of whom 20 have been reactivated and 10 transferred to resigned)	20	
Reactivated	1	
New members, April 21 to October 6, 1958	132	5161
Resigned	47	
Inactive	1	
Dropped	8	
Deceased (reported since April 21, 1958)	6	62
Total October 6, 1958		5099

Dues unpaid—As of October 1, 1958, the following dues were unpaid:

Owe for 1958	232
Owe for part of 1958	6
Owe for 1957 and 1958	147
Owe for part of 1957 and all of 1958	6

It was reported on May 4 that 148 persons had not paid dues in full for 1956 and for the years subsequent thereto. In accordance with the instructions of the Executive Committee, these people were urged to continue their membership in AGU; 20 have paid their dues in full and are again members in good standing, ten paid for 1956 with a request that their names be entered as resigned, and 118 have been dropped. It would thus appear that our effort to restore as many of these people to good standing as possible was not by any means fruitless.

Deaths—The following six deaths have been reported to the office of AGU since our last meeting: Robert L. Pendleton, June 23, 1957; Albert C. Hornady, July 5, 1957; Harry O. Wood, February 4, 1958; Victor H. Jones, March 6, 1958; Townsend Cromwell, June 2, 1958; Willie O. Byrd, July 6, 1958. Fr. Pierre LeJay (not a member), who was in the United States for the ICSU meeting early in October 1958, died October 11, 1958, en route home.

Finances—Below is a brief statement of our assets as of October 1, 1958, in comparison with the last two years.

	Oct. 1, 1958	Oct. 1, 1957	Oct. 1, 1956
Cash balance	$9,097	$17,728	$18,216
* Permanent Fund	15,000	14,055	13,075
Emergency Fund	1,000	1,000	1,000
T. M. & E. Award Fund	1,335	1,288	1,268
Russian Translation Fund	11,188	40,067	...
† Conference on Mechanisms of Precipitation Formation	25,000	...	...
Totals	$62,610	$74,138	$33,559

As noted above, the provisional budget was approved by the Executive Committee by mail ballot. This was essentially the firm budget based on our own funds and an anticipated grant of funds to help us meet our current deficit. The budget necessarily had to be incomplete because of the incomplete plans for the new journal and the lack of knowledge of the size of the grant which we ultimately will receive from the National Science Foundation. The Budget Committee has now reviewed the budget in the light of informal word received from the National Science Foundation on these matters. The framework of the approved provisional budget covers the essentials for our normal operations, taking into account the $2.00 increase in dues approved by the Executive Committee beginning January 1, 1959.

A financial statement for the year ending last June 30 has been submitted to the Audit Committee and will be presented for action at this meeting.

Office staff and jobs—Our office staff consists of full time members as follows: James J. Capello, Ethel G. Sanders, and Carol Cameron Akers, under the direction of Waldo E. Smith, Executive Secretary. Part-time staff members include Glenda Quinn Olmstead (about half time) and Barry Modlin (a student whose time is variable depending on the pressure of his school work). In addition, we have the full-time services of an Antioch College student, R. Patrick Conner, who began working on July 28 and will continue through the balance of this year. Mrs. James A. Peoples, Jr., is being employed as full-time editorial assistant to the co-editors, as noted above, to look after the affairs of the JGR editorial office established at Lawrence, Kansas.

Quarters—We are now occupying six rooms at the American Association for the Advancement of Science, having added on October 1 a small room to take care of additional space required in connection with the new publication plan, the work on the Russian translation project, and in connection with other grants. Our lease expires June 30, 1959; well before that date we will enter into negotiations for continuation if this is possible. Rental rate will probably be $4.75 per square foot per year instead of $4.00 as at present.

International matters—The Committee on International Participation (J. W. Joyce, Chairman) will make a separate report on the international situation. The report of this Committee was published in the August 1958 issue of the *Transactions* (pp. 765–766) and has elicited no comment from the membership except a communication from B. F. Howell, Jr., immediately following the presentation of the report at the Executive Committee meeting last May. It is anticipated that the Chairman will offer further recommendations for action.

We understand that the Finns are progressing with plans for the Twelfth General Assembly of IUGG to be held at Helsinki, Finland, July 25 to August 9, 1960. We should begin actively to prosecute our plans for participation, and some Sections, in fact, have taken steps to set up committees to monitor spontaneous papers.

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* Does not include accumulated interest on $2368 of U. S. Savings Bonds. The mature value of these bonds is $3200, $2500 of which mature December 1, 1958. Unless there are other instructions from this Committee, this amount will be added to one of our building and loan accounts at the time of maturity.

† Report on this item is given under Meetings below.

A general assembly of the International Council of Scientific Unions was held in Washington, October 2-6, 1958, and will be reported on later.

Meetings—It was deemed that the annual meeting held May 5-8, 1958 was an outstanding success. Our registration totaled 1249. Plans are developing for the Fortieth Annual Meeting to be held May 4-7, 1959.

The Pacific Northwest Regional Group will hold its annual meeting in Portland, Oregon, November 13-14, 1958. Vice President Berkner had planned to attend this meeting and to address an evening session on the subject "Scientific exploration of space." Berkner expects to go to the Antarctic early in November, and has made arrangements with W. H. Pickering of the Jet Propulsion Laboratory to speak on the same subject. Taking the place, as he will, of the Vice President, it is anticipated that AGU will defray his expenses unless objection is offered here.

The Section of Geodesy has established a Committee on Geodetic Applications of Artificial Satellites, and is planning a Conference on Contemporary Geodesy to be held at Cambridge, Mass., in the first week of December 1958. On June 24, after the plans for the conference had taken form, an application for a grant was filed with the National Science Foundation. The original application included about $7000 for the participation of foreign scientists, but in consultation with the Foundation this factor was eliminated, reducing the grant application to about $6800. We have informal word that the grant will be forthcoming in due course, and plans are proceeding.

The AGU is joining Section O (Agriculture) of the AAAS in the sponsorship of a symposium on water at the meeting of the AAAS in Washington between Christmas and New Year's, and also the U. S. National Committee for IGY on sessions related to the work of the IGY.

The annual meeting of the Pacific Southwest Regional Group will be held at Stanford University, February 5-6, 1959.

The Committee on Cloud Physics of the Section of Meteorology has had plans for a second conference under study for some time, and recently the National Science Foundation has approved a grant of $25,000 to cover the cost of the conference plus the cost of publication of the results presumably as one of the monograph series.

Statutes and By-Laws—As noted above, the ballot concerning the changes in the Statutes was mailed out on August 11, and the ballots were tallied on September 15 by the Committee of Tellers. Concomitant changes in the By-Laws were tentatively approved at the Executive Committee meeting on May 4, 1958, published in the August issue of the *Transactions* in accordance with the requirements of the Statutes, and are now to be placed before the Executive Committee for final action to effectuate the changes. Recommendation will be made later for this action.

Nominations—Nominating Committees for the Union and the Sections have completed their work, and the reports of all will be given later. The nominations for Union officers have been presented informally to the President of the National Academy of Sciences for concurrence or comment, and word of approval has been received.

Geophysical abstracts—President Ewing has appointed John Lyman (Chairman), Werner A. Baum, J. W. Joyce, John C. Reed, and Arthur H. Waynick as a committee to study the problem of abstracting geophysical material and seeing how this may tie in with the general programs of abstracting, both on the national scene and on the international scene, that are now under consideration. A report will be presented later.

Metric system of measure—At the meeting of the Section of Geodesy last May a resolution was passed relative to the adoption of the metric system by the United States, and it was reported at the business meeting of the Union subsequently as a resolution of the Section. In response to this, President Ewing has appointed Floyd W. Hough as Chairman of a Committee on Adoption of the Metric System in the United States to study the desirability of taking positive action to replace eventually in the United States the present English system of weights and measures and to substitute therefor the Decimal or Metric System.

American Geological Institute—Our representatives on the Board of Directors of the AGI are now James R. Balsley, Jr., and Walter H. Bucher.

Office of Critical Tables—George R. Tilton has been designated by President Ewing to serve as our representative on the Advisory Board of the Office of Critical Tables.

Miscellaneous—At the meeting of the Executive Committee on May 4, proposals were offered independently by Earl G. Droessler and Gerald J. Miatech that a suitable memorial be established in honor of the memory of Father James B. Macelwane, S.J., who at the time of his death was President of the AGU. President Ewing has appointed Droessler to explore this matter and report back with the possible result of the establishment of a formal committee.

Before the second session of the 85th Congress, the proposal for the establishment of an Institute of Geophysics in Hawaii again became active. AGU had been among the early proponents of the establishment of such an Institute, and upon reactivation of this bill in Congress a number of letters were written by the General Secretary and the Executive Secretary in the interest of the passage of the bill. The bill, however, was not passed and will be before the next Congress. It is hoped that action might be taken by that Congress to establish this greatly needed scientific facility.

The AGU also sent its endorsement of H.R. 13247, a bill in support of education in science through fellowships, scholarships, loans, and other means.

The Union was invited to send representatives to various functions during this interval, including the inauguration of the seventh President of the University of Southern California (George Tunnell of UCLA designated), the inauguration of the new President of Lafayette College (James L. Dyson, our representative), the inauguration of the twelfth President of Rensselaer Polytechnic Institute (Roland Beers designated), the inauguration of the fourteenth President of Wagner Lutheran College, the inauguration of the third President of Queens College in New York, and the dedication of Purdue University's new Memorial Center.

John R. Coash, Paul M. Pepper, Howard J. Pincus, and C. Warren Thornthwaite served as our representatives at the Second Bowling Green Conference on

Education and Professional Standards held at Bowling Green State University in Ohio on June 24–28, 1958. One of those attending (Thornthwaite) is a member of our Committee on Education.

AGU has responded to inquiries from educational and other institutions and individuals with regard to various matters pertaining to geophysics, in many cases with respect to educational facilities available and to the scope of geophysics.

A. Nelson Sayre, *General Secretary*

Action on the General Secretary's report—The report was accepted.

With regard to the maturing of $2500 worth of U. S. Savings Bonds Series F, the full confidence of the Executive Committee was expressed in the General Secretary and his advisors to invest this money in accordance with their best judgment.

With respect to the fact that W. H. Pickering of the Jet Propulsion Laboratory of the California Institute of Technology will take the place of Vice President Berkner in addressing the Pacific Northwest Regional Meeting in Portland, Oregon, November 13, 1958, it was approved that AGU should pay Pickering's expenses.

(President Ewing arrived at this point and presided for the rest of the meeting.)

Reports of Standing Committees

International Participation—Chairman J. W. Joyce gave the following information:

The third meeting of the Bureau of the International Union of Geodesy and Geophysics held at Moscow on July 21–24, 1958, is reported in some detail in *IUGG Chronicle 13.* There were 17 items on the agenda. He noted that General Secretary Laclavere announced that 1500 copies of the Toronto Assembly Transactions have been printed and that about 500 are being distributed.

The following remarks highlight and supplement the official IUGG minutes of the Bureau meeting.

As far as new memberships in IUGG are concerned, most of the remaining countries that may apply will probably be in the lower categories, with the exception of Red China. It looks as though Bulgaria will soon apply for adherence. As far as Chinese adherence is concerned, J. Tuzo Wilson, President of IUGG, visited the two Academies of Sciences of Peking and Taipei and reported briefly to Laclavere, Deacon, and Joyce during the Washington meeting of ICSU early in October 1958. He stated that if the Taipei application made it clear that it claimed to represent only the territory now controlled by the government of the Republic of China, the application which is now before the IUGG will in all likelihood be processed, but this might not be done until the General Assembly in 1960. Red China will apparently not submit an application as they refuse to sit down with "the other China." Laclavere plans to visit the two Academies in October 1958.

The *Chronicle* seems to be going over fairly well. Laclavere has received over a thousand replies to a questionnaire sent to its recipients, and practically all of them welcome it and some suggested improvements. In general, most of the instructions that were received as a result of the questionnaire and earlier meetings have been carried out. Every effort is being made to cut costs, and it will now cost about $3000 a year for printing, distribution, etc.

The IUGG Committee on Geophysical Bibliographies that was set up has not been able to meet as yet because of the wide geographical distribution of its members. Ray K. Linsley has agreed to serve as Chairman. If the AGU's committee on this subject has anything of interest to suggest, it should get into touch with Linsley so that he can take advantage of it. Joyce suggested that Linsley might well be a member of the AGU Committee on Geophysical Abstracting.

With regard to publication, the IUGG would like to try a few other publishers competitively in addition to Pergamon Press before deciding on any one.

The new categories adopted at Toronto will result in some additional revenue. IUGG will receive approximately $44,000 per year, as compared to ICSU's annual income of about $45,000.

The Bureau was not called upon to take any action on the draft text of the new Statutes and By-Laws other than to make additional suggestions.

The rules for symposia prepared by Joyce were discussed at Moscow, and after some modifications and additions by the Bureau, these are being sent to the members of the IUGG Executive Committee for their consideration. A list of 12 symposia is being considered for the Helsinki Assembly. Berkner expressed the view that IUGG has been spending a lot of money in publication and not getting enough in visible results. He urged that the AGU Executive Committee strongly support the Chairman of our Committee on International Participation, who is also on the IUGG Bureau and Executive Committee, in trying to improve the publication situation.

With regard to the Russian proposal for the establishment of award medals, Joyce noted that it is now agreed that two medals should be decorously bestowed at each General Assembly to two scientists for outstanding scientific work in geodesy and geophysics, one concerning the solid Earth and the other the hydrosphere and atmosphere.

There has been a considerable amount of discussion in the Bureau as to what the function of the IUGG should be at the close of the IGY. So far, the only concrete proposals are concerned with the holding of appropriate symposia and that the IUGG would serve as a point of coordination for possible future programs. If any AGU members have suggestions in this connection, it was urged that these be passed on to the Chairman of the Committee on International Participation for forwarding to the IUGG.

Attempts will be made to firm up agenda for the Helsinki Assembly well in advance of the opening date. The Finnish Committee is doing all it can to plan a good assembly. The IUGG Bureau has tentatively suggested that a registration fee be charged for all persons attending, at the same time cutting down social functions as much as possible to conserve funds.

The Finance Committee has indicated a possible deficit of about £25,000 for the triennium largely because of publication costs. This is based on Association and Union estimates recently received.

The next meeting of the Bureau will be held in Paris in September 1959. The Executive Committee and Finance Committee will both meet at the same time.

Chairman Joyce, in closing his remarks, reported that the report of the Committee regarding the recommended revision of the structure of the Executive Committee of the AGU to provide more effectively for the discharge of responsibilities as the U. S. National Committee for the IUGG, published in the August 1958 issue of the *Transactions* (pp. 765–766), elicited comments from only one person, B. F. Howell, Jr. Joyce is discussing his proposals with Howell to include those that are appropriate.

C. A. Whitten referred to an invitation on behalf of AGU to the International Association of Geodesy to hold a symposium on distance measuring equipment in Washington, D. C., during May 1959 in conjunction with the Annual Meeting of AGU. A motion was passed that the Executive Committee strongly endorse this plan and give any assistance that the AGU can.

Vice President Berkner reported that at the ICSU meetings two alternative attitudes were evident concerning termination of the IGY. (1) The IGY was organized and conducted with the encouragement of the Unions to obtain basic scientific data needed for the advance of geophysical sciences, these data were now amply coming in, in response to the expression of need by the Unions, and the Unions were amply competent to deal with the data through meetings, discussions, symposia, and publication. (2) The IGY organization should be continued to deal with the data. If, however, substantially all new data were handled outside of the Unions, the future usefulness of the Union comes into doubt.

Therefore, this difference in views raises a serious question as to whether the Unions should be strongly supported, or should disappear in favor of special committees. It was finally decided that there should be a Special Committee for Inter-Union Cooperation on IGY Results. International Geophysical Cooperation in research during 1959 (IGC-1959) will be continued under this Committee, but it was decided to close the IGY office late in 1959 so that this Committee would not be encouraged to act in place of the Unions. If we are going to have special committees, they should come, do their job, and then disappear. Berkner thought it would be appropriate if the Executive Committee of the AGU recognized the IGY meeting which is now planned for Washington in September 1959 as a series of symposia on IGY results and that AGU should act as one of the sponsoring agents of these symposia. He suggested that the Committee on International Participation communicate with General Secretary Laclavere and with the local arrangements committee, and make such arrangements as necessary to make the AGU a cosponsor of these symposia.

A motion was adopted that AGU, acting on behalf of IUGG, join enthusiastically in the sponsorship of the symposia dealing with IGY data to be held in Washington in September 1959 and that the Chairman of the Committee on International Participation be designated as a representative of the Executive Committee in making this arrangement.

Berkner reported that each Union is now required to designate a fixed representative to ICSU over any interval of three years. The Executive Board of ICSU has now become a permanent board operating between meetings.

ICSU has adopted a policy of political non-discrimination, that is, ICSU will recognize any *bona fide* academy, research council, or national committee in any area in order to bring all of the world into the field of ICSU and its Unions.

W. W. Atwood, Jr., referred to a provisional report on the recent ICSU meeting, a copy of which he had turned over to Berkner. This 28-page mimeographed report will be quite useful to all who are concerned with ICSU and its Unions, particularly as it contains quite a number of the reports and actions taken by the Executive Board at the meeting and perhaps would not appear in the actions of the assembly as such. Berkner asked that copies be supplied to all members of the Executive Committee.

The Executive Secretary noted that we have before us the report of the Committee on International Participation published in the August 1958 issue of the *Transactions* (pp. 765–766) and inquired as to what is the next step towards implementation of this report. It involves substantial reorganization of AGU, especially the constitution of its Executive Committee.

Joyce said that one of the principal points raised in Howell's comment was that the membership of the Council as proposed was not sufficiently under the control of AGU, and therefore his Committee should reconsider the status of the various members that have been proposed. Joyce felt that the various units that are represented on that Council are appropriately there, and the question is which should be voting members and which non-voting. He suggested that the three Government agencies listed as voting members now be removed from this, which would leave only the members at large to be appointed by the National Academy which might be quite apart from AGU. Since these would probably be selected by the Division of Earch Sciences, it was felt that AGU would in all probability have members in all this representation.

Berkner suggested that it would be proper to instruct this Committee to consult with Howell and re-draw the paper, and then see if it would meet the approval of the Research Council, with the object of circulating a final paper.

L. T. Aldrich stated that the report which we had from the Committee last spring should include the alternative when presented before the membership.

President Ewing noted that, since this is a matter which some people think is the most important function of the Union and there is so little comment on it, Howell and Aldrich serve as consultants to the Committee. This was agreed to.

Editorial and Publication—Chairman Sayre stated that this Committee will continue until the new publication plans have been implemented.

Peoples called attention to the promotional leaflet announcing the new monthly *Journal of Geophysical Research* which will be inserted immediately inside the front cover of the October issue. He expressed the belief that the improvement in the new journal will be gradual rather than sudden.

Abelson reported that things have been running smoothly with the new journal as the editors have simply accepted the reviewed material of both *JGR* and AGU. The big problem now is to see that the good material comes to the journal and that we should all be on the lookout for suitable material.

The Executive Secretary noted there will be a report of the Committee on Budget a little later relative to publication. Applications for grants have been filed with the National Science Foundation in this connection, one covering a deficit of $15,000 for the current calendar year and another covering a series of grants totaling about $237,000 over a five-year period. We have informal word that the National Science Board has approved a substantial grant for the first two years plus our deficit, which we should receive soon. We have proposals from three printers for printing the new journal, and it is expected that a decision with regard to the printer will be made in ample time so that the January issue will be on time.

Monograph Board—President Ewing noted that he is seeking a Chairman for the Monograph Board.

Berkner noted that some monographs of excellent quality frequently must have extensive illustrative material that is costly to print, causing publishers to avoid them, and that these might be undertaken by AGU in the monograph series to ensure publication. The Executive Secretary mentioned three projects that are now developing, but that formal application for a grant for the Monograph Series has yet to be filed with the National Science Foundation. Before the National Science Foundation will seriously consider making such a grant, we need to have the Monograph Board formally appointed and some actual plans for monographs that we want to put into this series. Ideas for definite monographs were requested. Landsberg noted there is no oversupply of good material and felt that if AGU would use its monograph series as an integral part of things presented at AGU meetings and conferences, being sure that the quality is excellent, then the monograph series would provide an excellent and prompt outlet. Abelson noted that the Monograph Board should be largely a policy-making group that would have to have energy to seek out the best advice on a prospective monograph and select the proper technical editor for each.

The meeting recessed at 10h 40m and was resumed at 11h 00m.

Russian translation project—It was noted that Nos. 1 to 5 and 7 of 1957 of *Izvestiia* have now been received, No. 7 only within the last two or three days. On October 16 a conference was held by the General Secretary and the Executive Secretary with I. R. Maxwell and D. J. Raymond of Pergamon Press, and with Paul S. Feinstein of the National Science Foundation sitting in. At this meeting the difficulties and delays were reviewed, it being pointed out that AGU is dissatisfied not only with the increasingly delayed delivery schedule but also with respect to the quality of the translations although there has been some improvement in recent numbers. Maxwell made the following proposition:

"1. Pergamon Press is willing and able to continue to translate and issue this journal for and on behalf of the American Geophysical Union.

"2. Recognizing the dissatisfaction because of late delivery of the 1957 issues which were wholly and completely due to lack of skilled and experienced translators in the area and translation editors and because the Russians increased the journal by some 30 pct, that is, approximately 500 additional pages, and realizing that in spite of this Pergamon Press has been at fault formally in that the issues have been late, Pergamon Press proposes that the arrangements from 1958 be predicated on the following special conditions in addition to the usual contractual arrangements that may be required:

"(a) The Russian Translation Board and Pergamon Press to agree on a publication schedule for the issues of 1958. However, the Russian Translation Board may, in the absence of agreement by Pergamon Press, fix such time schedule as it considers reasonable for the publication of these issues.

"(b) Pergamon Press will accept a penalty clause of $500 for each issue that it may be late in issuing in accordance with the publication schedule laid down or agreed upon with the Russian Translation Board. This penalty clause is automatic if any issue is more than 30 days late after a stipulated date with the Committee.

"(c) AGU may terminate this contract without advance notice at any time that Pergamon Press fails to publish any issue within the date plus 30 days agreed or stipulated by the Russian Translation Board.

"(d) In the event of AGU exercising the right of cancellation, Pergamon Press agrees and warrants the orderly handover of all subscription records, the translations in the pipeline, illustrations, and do all such things as they may be required to do by the Russian Translation Board of the AGU to ensure the continued publication of the journal with a minimum of dislocation, effort, or expenditure on behalf of AGU.

"(e) Pergamon Press is making this offer to AGU because they believe that the know-how and experience that they have acquired in the past year is too valuable a translation asset in this area for it to be thrown away and discarded. We firmly believe that AGU will be completely satisfied with the translation and the speed that is being made available for 1958, and, in addition, should this not prove to be so and should AGU wish to take on the job itself, then this arrangement would give the necessary time to set up an alternative mechanism for doing the job better and quicker than it has been hitherto."

General Secretary Sayre, in reviewing the Pergamon Press difficulties, indicated that Maxwell had noted that they have had a great turnover in translators, using as many as 200, that at the present time his stable of translators is operating satisfactorily and the translations for 1957 are complete, and that without authorization Maxwell has started the translation of *Izvestiia* for 1958. Sayre, indicating that he neither espoused nor rejected Maxwell's proposal, felt that we should give it due consideration, taking account that if we undertake this ourselves we will probably have to go through much the same difficulties that Pergamon Press has found. Pergamon Press feels that their performance on this endeavor has given them a bad name and that they would like to have opportunity to overcome this by better performance in respect to *Izvestiia* for 1958. It was pointed out that an essential thing of the memorandum is a penalty clause of $500 for late issues and also the termination clause if the project does not develop in a satisfactory way. After extensive discussion, especially with regard to quality, it was felt that we could set up our own project with a translation editor and stable of translators in much the same way as the American Institute of Physics has set up their project for the *Journal of Experimental and Theoretical Physics* with J. George Adashko as their translation editor. In this connection we will seek the concurrence of the Russian Academy of Sciences and make an effort to secure originals of figures in order to improve reproduction. Vice President Berkner noted that he feels that AGU should not embark upon anything that will in any way jeopardize our new *Journal of Geophysical Research* and the Monograph Series.

A motion was made and passed unanimously that it is the sense of the meeting that the Russian Translation Board should make all possible efforts to use another translation agency for the 1958 *Izvestiia*.

Budget—Chairman John C. Reed presented the report of the Committee on Budget as set forth in Appendix 1. Noting that this now involves the numerous developments that have taken place since the provisional budget was submitted to the Executive Committee in early July, the budget as set up contemplates a grant from the National Science Foundation for publication of the *Journal of Geophysical Research* which actually is not yet in hand but which should be received at least in large measure according to informal advice received.

Nominations—Chairman L. H. Adams noted that the rule concerning the number of nominees was suspended for the elections of 1956 by a mail ballot of the Executive Committee during July. He offered the following nominations for and on behalf of his Committee for the three-year period commencing with July 1, 1959: For President, Lloyd V. Berkner; for Vice President, F. W. Reichelderfer and George P. Woollard; for General Secretary, John Lyman and A. Nelson Sayre. The report was accepted.

The following nominations were submitted by the Committees on Nominations of the Sections for the three-year period starting July 1, 1959:

Geodesy—Charles Pierce for President; Floyd W. Hough for Vice President; Buford K. Mead for Secretary
Seismology—L. M. Murphy for President; J. A. Peoples, Jr., for Vice President; B. F. Howell, Jr., for Secretary
Meteorology—Thomas F. Malone and B. Haurwitz for President; Gordon E. Dunn and E. W. Hewson for Vice President; Woodrow C. Jacobs for Secretary
Geomagnetism and Aeronomy—L. R. Alldredge for President; C. T. Elvey for Vice President; J. H. Nelson for Secretary
Oceanography—John Lyman and Walter H. Munk for President; Arnold Arons and D. W. Pritchard for Vice President; Eugene C. La Fond and Dale Leipper for Secretary
Volcanology, Geochemistry, and Petrology—Alfred O. C. Nier for President; Francis J. Turner for Vice President; Irving W. Friedman for Secretary
Hydrology—Harry F. Blaney and Walter B. Langbein for President; Wm. C. Ackermann and William E. Hiatt for Vice President; Charles C. McDonald and Ralph N. Wilson for Secretary
Tectonophysics—Patrick M. Hurley for President; L. B. Slichter for Vice President; H. Richard Gault for Secretary;

President Hess of the Section of Tectonophysics noted that there are no nominees for two members of the Section's Executive Committee and that he will arrange with the Committee on Nominations of the Section to make them.

The nominations submitted were accepted.

The following nominations were submitted by the Committee on Nominations of the two regions cited for the three-year period commencing July 1, 1959:

Pacific Northwest Regional Committee: Representing Geodesy—Donald J. Brown and Ector B. Latham; representing Seismology and Tectonophysics—Mark F. Meier and Peter Misch; representing Meteorology—Lenard Bissell, Carlton Jencks, Donald W. Keuhl, and Melvin J. Ord; representing Geomatism and Aeronomy, and Volcanology Geochemistry, and Petrology—Keith E. Anderson and Peter B. Boyer; representing Oceanography—Nedevia Bethlahmy and Wayne V. Burt; representing Hydrology—Charles L. Barker, Thomas H. Campbell, Harold D. Hafterson, Albert M. Moore, Calvin C. Warnick, and R. A. Work.
Pacific Southwest Regional Committee: Representing Hydrology—Arthur F. Pillsbury, Joseph F. Poland, and David K. Todd; representing Oceanography—Henry W. Menard and Jacob B. Wickham; representing Meteorology—W. D. Duthie, Eugene Bollay, and Robert E. Holzer; representing Geomagnetism and Aeronomy—E. H. Vestine

The recommendations for the Regional Committees were accepted.

The Executive Secretary reported that no nominations have been received from the North Central Regional Committee and that perhaps we should consider this Region as no longer operative if no nominees are received by June 30, 1959, as it has not been active for some time.

Statutes and By-Laws—A motion was passed taking final action to approve the changes in the By-Laws approved at the Executive Committee meeting of May 4, 1958, and published in the August 1958 *Transactions* (pp. 764–765).

A suggestion was made to change the Statutes to eliminate the present provision that non-citizens of the United States can not vote. Action on this was postponed pending the receipt of a report from the Committee on International Participation.

Meetings—Chairman P. H. Abelson announced that President Ewing would be expected to present a presidential address on the evening of the Bowie Medal Award at the Annual Meeting. He also noted that the Committee always welcomes suggestions with regard to plans for the meetings.

The Executive Secretary reported that there are recurring inquiries from members as to why the Annual Meetings are not held in other cities. Other members have asked whether we could arrange the meetings so that they are entirely under one roof. These questions should constantly be kept before us. With regard to meeting under one roof, this would mean going to a hotel, which would involve luncheons, dinners, and other functions and frequently not too intellectual an atmosphere. The feeling was that we should continue to hold our meetings with headquarters at the National Academy of Sciences.

Membership—Chairman Earl G. Droessler was not present but had indicated that he had no report other than that shown by the membership statistics in the General Secretary's report. Vice President Berkner called attention to the substantial increase in corporation memberships, most of which were the result of about 20 letters that he sent out in the spring. He urged others also to write letters to their friends in key positions in industrial and commercial concerns that are involved in any way in geophysics.

The suggestion has been made that, in addition to corporation membership at $100 a year, we might have other memberships such as sustaining memberships and contributing memberships, say, at $1000 and $500 a year. A motion was adopted that the Committee on Statutes and By-Laws take steps to make amendments in the Statutes and By-Laws for provision of such memberships as these, the report to be brought in at the next meeting of the Executive Committee.

Audit—The report which Chairman A. G. McNish submitted on behalf of the Committee on Audit as set forth in Appendix 2 was accepted.

Reports of Special Committees

Cosmic-Terrestrial Relationships—Chairman E. H. Vestine was not present, but it was noted that a recent report has been submitted by him. This is now in the hands of the editors of the *Journal of Geophysical Research* to decide whether it is proper material for that journal or whether it should be published in the *Transactions.*

Award of William Bowie Medal—Chairman Walter H. Bucher reported that the Committee has selected Walter M. Elsasser as the Twenty-First Recipient. This report was accepted. It was noted that plans are being made for a dinner preceding the formal award of the Medal on the evening of May 5, 1959, and that this dinner will probably be held at a hotel as in the spring of 1958.

Tellers—Chairman J. H. Nelson submitted the report of the Committee with regard to the recent ballot on changes in Statutes as indicated in Appendix 3. President Ewing expressed great satisfaction to find that so large a number voted so strongly in favor of the new publication plans.

Education—President Ewing reported on behalf of Chairman John E. Nafe who could not attend, and noted that attempts to hold meetings of this fairly large committee have not been successful, that the Chairman had circularized the members to determine whether they would rather disband or have a smaller committee and found the vote was indecisive, and that he requested instructions as to what should be done. Hess, a member of the Committee, noted that the Committee has never been able to get together to define exact objectives and that the present broad scope makes the Committee rather ineffectual. The President requested comments from those who felt that this group has useful work to do. Langbein mentioned that there is no unified training in hydrology, that it is now on-the-job training, and that he felt AGU might be of some help. The Executive Secretary gave a brief history of our endeavor in this regard, noting that this was the outgrowth of frequent inquiries to the office for information and that it stems back originally to the survey made in 1945 and published in the December 1945 issue of the *Transactions*, with a supplement in August 1946, Geophysics is a late comer, is rather diffuse on most college campuses. The National Science Foundation felt that our plan for a new survey on education in geophysics, rather similar to the 1945 plan, was superficial and that we should go more deeply into the problem, citing the work that the mathematicians had done in relation to the graduate education in mathematics. Atwood referred to the success of the educational programs of IGY. W. C. Jacobs expressed the thought that it is important that AGU be equipped to advise on these matters, noting that the Air Force has a good program on training officers in the broader aspects of geophysics and that AGU would be a logical Air Force contact if we had material available that would be of help. Berkner noted a substantial sentiment in universities to reorganize training in the Earth's sciences and that there has been some pulling together of the geophysical sciences, perhaps to a certain extent under the influence of the IGY. He felt that we need a high-level man to undertake a survey like this, one with enthusiasm to head up such a committee and work with schools that are reorganizing their courses. He mentioned certain names that might well be sought. Peoples noted that at the undergraduate level the emphasis for most fields of geophysics should be on mathematics and physics rather than on geophysics but that in geophysical engineering this might not be necessary. Berkner expressed the thought that mathematics should draw its problems from the field in which the student is specializing, and that mathematics should appropriately be developed around geophysical problems. Howell suggested we should find out how members of the Union had entered geophysics as a profession, noting that relatively few are trained as geophysicists. Hurley mentioned that he is also a member of the Committee on Education and is involved in the work at the Massachusetts Institute of Technology in building up geophysics there, and he has the feeling that a questionnaire will serve no useful purpose. He indicated that MIT is developing a monograph series for supplementary reading for education in high schools to orient students who have natural interest or inclination in geophysical curricula. His feeling was that the Committee should disband. Peoples suggested that it would be helpful if this Committee could put out a brief report on what universities like MIT and Princeton have done to unify geophysics on our campuses. Abelson expressed the thought that a good deal depends upon the man who is Chairman. If we find one who feels that something useful can be done, have him go ahead; if not, the Committee should be disbanded. No action was taken.

Geophysical Abstracts—Chairman John Lyman was absent, and John C. Reed, a member of the Committee, reported on his behalf. He noted that the Committee has prepared a report on which they sought the cooperation of the American Meteorological Society. This would involve an expansion of the present *Meteorological Abstracts* to become *Meteorological and Geo-*

physical Abstracts. We might become cosponsors and lend moral support and aid in securing grants and other funds for support but leave the administration of the project in the hands of the American Meteorological Society with a joint cooperating committee. No report has yet come in from the AMS on this plan. The report of the Committee appears in Appendix 4.

Adoption of the Metric System in the United States—Chairman Floyd W. Hough noted that this is a new Committee and is just becoming organized.

Macelwane Memorial—It was noted that this is not a formal committee but simply a move in which President Ewing and Earl G. Droessler are joining to see what might be undertaken.

Reports of Sections

Geodesy—Vice President Charles Pierce noted that President Schmidt has no formal report but mentioned that the Committee on Geodetic Applications of Artificial Satellites has arranged a Conference on Contemporary Geodesy to be held at Cambridge, Massachusetts, December 1 and 2, 1958, with the cosponsorship of the Smithsonian Astrophysical Observatory and Harvard University. AGU expects a grant from the National Science Foundation in the amount of $6800 to aid in defraying the costs of this conference and the compiling and publication of the record.

C. A. Whitten again referred to the symposium to be held by the International Association of Geodesy on distance measuring equipment in Washington, D. C., in conjunction with the Annual Meeting, and AGU's responsibility to help to make it a success. He noted that a group met in Munich, Germany, last July for the establishment of a Committee on Earth Tides sponsored by the International Association of Geodesy and the International Association of Seismology and the Earth's Interior. W. D. Lambert, who attended the meeting in Munich but who was not present, has raised the question as to what extent other Sections, notably Oceanography and Hydrology, might be interested.

Meteorology—President Landsberg announced that the Committee on Cloud Physics of the Section is arranging a Conference on the Mechanisms of Precipitation Formation which will be held in June 1959 at the Woods Hole Oceanographic Institution. A grant of $25,000 has recently been received in support of this conference to bring foreign participants and to compile and publish the results.

Oceanography—Secretary D. W. Pritchard mentioned the International Congress on Oceanography which is to be held in New York in September 1959.

Hydrology—W. B. Langbein, alternate for President Linsley, noted that the international symposia of the International Association of Hydrology had been outstandingly successful and that these give an opportunity to become more acquainted with developments in specific fields than the reports presented at the general assemblies. The Darcy symposium held in France in 1957 and the one held in Chamonix, France, in September 1958 on the physics of ice movement were excellent. A symposium on forests and waters will be held in Germany in 1959. The Association is rather hard put financially with regard to publication. The publications do not receive as wide circulation as they should. The Association is issuing a quarterly bulletin on hydrology which they feel should help to overcome this difficulty.

National Research Council reports

It is now noted that Frank Press is the representative of AGU in the Division of Earth Sciences and that John N. Adkins is Chairman.

New Business

The General Secretary noted that presumably we will soon receive a substantial grant from the National Science Foundation to aid in our publication plans, and requested instructions as to where this money should be deposited to be most safe. Our present arrangement is to put our excess funds in the savings account in the Riggs National Bank, but these are not guaranteed or insured beyond $10,000. Many building and loan associations, both in the Washington area and elsewhere, are paying interest up to four per cent, but they are guaranteed only to the extent of $10,000 each. Budget Chairman Reed suggested putting this money in Government bonds as the guarantees elsewhere are not adequate. Vice President Berkner felt that we should investigate the possibility of purchasing 90-day or similar Treasury notes for monies needed at an early date that carry interest from one to three per cent, that can be cashed at any time, and that do not flucuate in value. A motion was adopted instructing the General Secretary to invest such monies as seem appropriate in Goverment bonds or Government guaranteed deposits, and, for monies needed at an early date, in 90-day or similar Treasury notes.

The Executive Committee expressed its appreciation for the work done by the two coeditors of the new journal, P. H. Abelson and James A. Peoples, Jr., and the Executive Secretary in getting the new publication plans under way.

Adjournment—The meeting adjourned at 13h 15m.

A. Nelson Sayre, *General Secretary*
Waldo E. Smith, *Executive Secretary*

Appendix 1—Report of the Committee on Budget for the Fiscal Year Ending June 30. 1959

John C. Reed, Chairman
E. H. Bramhall L. O. Quam

Your Budget Committee prepared a provisional budget for 1959 that was presented to the Executive Committee on May 4, 1958. Because of actions of the Executive Committee in regard to dues, publications, and other items, that first budget for 1959 required substantial revision. A revised budget was laid before a meeting of some of the officers of the American Geophysical Union on June 18 by Bramhall and that revision, with one minor change, was sent to the Executive Secretary on June 26. It was approved as a provisional budget by the Executive Committee in July.

Events since June make possible another revision of the budget now with fair assurance that some heretofore doubtful areas are stabilized. However, some of the developments that greatly affect the budget have happened so recently that the Chairman of the Budget Committee has not had an opportunity to consult with the Committee in regard to them.

Thus the revised budget here presented is, in respect to the latest changes, entirely the responsibility of the Chairman.

Regular Operations

Estimated receipts

Membership dues			
4100 members at $10	$41,000		
100 student members at $3	300		
23 corporation members at $100	2,300		
Dues in arrears, 500 members at $8	4,000	$47,600	
Publications			
Sales and subscriptions			
Journal of Geophysical Research, 1000 at $16	16,000		
Transactions, 1000 at $4	4,000		
Sales of back numbers	1,000		
Reprints	3,000		
Page charges (½ year), 800 at $15	12,000		
Advertising	14,000	50,000	
Other			
National Research Council grant	400		
Interest on funds on deposit	3,600		
Geophysical Monograph No. 1	800		
Geophysical Monograph No. 2	5,000		
Royalties (microcards and reprinted *Transactions*)	200		
National Science Foundation grant[1]	146,000		
Miscellaneous (includes contributions to permanent fund)	500	156,500	$254,100

Estimated expenditures

Transactions of 1958 (6 mos. 3 issues)			
Preparation, proof reading, etc. (chiefly salaries)	$4,400		
Printing (3 issues at $5,500)	16,500		
Mailing	700		
Editors	700		
Reprints	1,400		
Advertising agent's commission	1,500	$25,200	
Transactions of 1959 (6 mos. 2 qtrly. issues)			
Preparation, proof reading, etc.	600		
Printing (2 issues of 24 pages each)	1,500		
Mailing	300	2,400	
Journal of Geophysical Research (6 months, 6 issues, 200+ pages each)			
Preparation, proof reading, etc. (chiefly salaries)	16,000		
Printing (6 issues)	43,560		
Cover	300		
Mailing	1,500		
Editor and assistant	3,000		
Reprints	4,000		
Advertising agent's commission	2,800	71,160	
General Office expenses			
Rent	4,300		
Salaries and Social Security	18,800		
Retirement contribution	1,200		
Stationery and supplies	2,000		
Office equipment	2,000		
Postage and communications	2,500	30,800	
Expenses for meetings			
Annual	1,500		
Regional	200	1,700	
Miscellaneous			
Expenses for Sections	100		
Expenses for Committees	100		
Travel of Officers	1,000		
President's fund	100		
Directory Reserve	1,300		
Monograph No. 2	6,500	9,100	$140,360

Total expenditures	$140,360
Total receipts	254,100
Estimated surplus[2]	$113,740

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[1] Of the $146,000, $46,000 is estimated to be needed in fiscal 1959, $66,000 in 1960, and $34,000 in the first half of fiscal 1961.

[2] The apparent surplus must be considered in the light of the expectation that large amounts will be needed for publications in 1960 and 1961.

Appendix 2—Report of the Committee on Audit for the Fiscal Year Ending June 30, 1958

A. G. McNish, Chairman
E. B. Roberts R. H. Weightman

Your Committee on Audit has examined the books of the American Geophysical Union for the fiscal year ending June 30, 1958, and finds them in agreement with the statement of the Union's finances supplied by the Executive Secretary.

At the beginning of the current fiscal year the cash assets of the Union amounted to $80,832.25, including Series F bonds and deposits in the Permanent Fund. In addition, bills receivable amounted to $11,954.97, making the total assets of the Union $92,787.22. The liabilities of the Union, including checks outstanding, bills payable, and commitments, amounted to $54,625.02, leaving a surplus of $48,987.46. At the close of the present fiscal year the assets of the Union, including bills receivable, amounted to $77,687.38, and liabilities amounted to $31,328.08, leaving a surplus of $46,359.30. A large part of this decrease in assets resulted from expenditures against the translation project, with a corresponding decrease in liabilities. The healthy aspect of the Union's financial condition is reflected in the small change in the balance between these figures.

Your Committee has examined the books recording the financial transactions of the Union, and, although a completely detailed audit has not been made, the Committee has spot-checked the records and examined large items with sufficient care that we can assure you of the soundness of this report.

Your Committee wishes to compliment the office of the Executive Secretary for the excellent condition and meticulous detail in which the financial records have been kept. Even minor contributions by members to the Permanent Fund of the Union, many of which amounted to only $1 or $2, have been properly entered in the records of the Union with the names of the donors of these funds.

Operating Statement

(Fiscal year ending June 30, 1958)

Receipts

National Research Council grant for publication			$400.00
National Research Council grant for IUGG meeting			800.00
Income			
Dues, 1955 and earlier	$61.20		
1956	560.17		
1957	4,034.38		
1958	34,194.25		
1959 et seq.	212.08		
Corporation memberships	3,000.00	$42,062.08	
Sales of publications			
Transactions	$15,231.13		
Reprints	5,506.86		
Geophysical Monograph No. 1	983.59[a]		
Geophysical Monograph No. 2	1,379.00[a]		
Miscellaneous	44.00	23,144.58	65,206.66
Contributions to Permanent Fund			457.00
Interest on Permanent Funds			469.97
Interest on T. M. and E. Award Fund			47.10
Interest on deposit with Interstate Building Association			374.36
Interest on deposit with Riggs National Bank			769.48
Advertising receipts			8,707.29
Sale of equipment (2 fans)			50.00[a]
Microcard royalty			123.86[a]
Conference on Atmospheric Chemistry			200.00[a]
IGY Bulletins			6,261.38[a]
Miscellaneous			110.71
Total receipts			$83,977.81

Disbursements

Publishing *Transactions*		
Printing	$33,630.96	
Preparing copy	7,667.97	
Honoraria to editors	1,275.00	
Mailing	1,394.14	
Advertising expense	80.37	$44,048.44
Reprints		2,333.81
General expenditures (office of the Union)		
Salaries (including Federal Social Security)	$17,725.97	
Stationery and supplies	1,652.34	
Postage and communications	1,566.28	
Office equipment	40.35	20,984.94
National Academy of Sciences pension plan		1,062.56
Expenses, Committee on Membership		19.60
Expenses, Section of Hydrology		41.59
Expenses, Meetings		
Annual Meeting	$1,588.03	
Regional Meetings	167.04	1,755.07
Investment, Deposited in Prudential Building Association, part of Permanent Fund		475.00[a,b]
Russian Translation Project		10,168.86[a]
Rent		3,728.04
IUGG meeting		809.54[a]
Bowie Medal		666.36
Travel		416.68
Geophysical Monograph No. 1		3.36[a]
Geophysical Monograph No. 2		1,280.18[a]
IGY Bulletins		7,271.83[a]
Conference on Atmospheric Chemistry		235.02[a]
Miscellaneous		1.05
Total disbursements		$95,301.93

[a] Non-budget items.

[b] This is actually a transfer of funds; the amount remains available to AGU.

Excess of disbursements over receipts

Disbursements (including transfer of $475 to Permanent Fund)	$95,301.93	
Adjustment for transfer	475.00	
Net disbursements		$94,826.93
Receipts (including special fund for Russian Translation Project)	$124,708.51	
Less balance in special fund for Russian Translation Project	30,561.34	
Receipts, regular AGU funds		94,147.17
Decrease in liquid funds, regular account		$679.76

Statement of assets and liabilities as of June 30, 1958 (see pp. 153–154 of Feb. 1958 *Transactions* for statement of assets and liabilities as of June 30, 1957)

Assets

Cash Reserve		
On deposit in Riggs National Bank	$42,409.47[a]	
On deposit in Interstate Building Association	10,238.47	$52,647.94

Permanent Fund			
Series F bonds purchased prior to July 1, 1958 (maturity value $3,200), at cost	$2,368.00		
On deposit in Northwestern Federal Savings and Loan Association as of July 1, 1958	10,127.52		
On deposit in Prudential Building Association as of July 1, 1958	2,429.47	$14,924.99	
Emergency Fund			
On deposit in Prudential Building Association as of July 1, 1958		1,000.00	
T. M. and E. Award Fund			
On deposit in Liberty Building Association as of July 1, 1958		1,335.20	$69,908.13
Bills Receivable			
Dues			
1958 only	$3,100.60		
1957 and 1958	1,392.00	$4,492.60	
Publications			
Transactions (including back numbers)	$203.77		
Subscriptions	223.00		
Reprints	1,567.41		
Miscellaneous	25.61		
Monograph No. 1	164.75		
Advertising	91.66		
IGY Bulletins	1,010.45	3,286.65	7,779.25
			$77,687.38
Liabilities			
Bills Payable and advance payments			
Dues in advance (1959 et seq.)	$247.68		
Subscriptions in advance (1959 et seq.)	314.35		
Misc. (mainly credits a/c overpayments)	204.71	$766.74	
Russian Translation Project commitment		30,561.34	$31,328.08
Surplus (Capital Account)			46,359.30
			$77,687.38

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[a] Riggs National Bank statement of June 30, 1958	$49,818.38
Less checks outstanding	7,408.91
	$42,409.47

Appendix 3—Report of the Committee of Tellers

The Chairman and several members of the Committee of Tellers met at the office of the American Geophysical Union at 09h on September 15, 1958 to open and count ballots. The following assortment of ballots was considered:

Total ballots received		2205
Rejected ballots:		
Ballots from non-citizens of the United States	33	
Ballots from members delinquent in payment of dues	7	
Defective ballots (unmarked)	6	46
Qualified ballots counted		2159

The result of the vote is as follows:

In favor of the change of publications plan	2081
Not in favor	78

The following members of the Committee participated in the counting of the ballots: Messrs. James N. Jordan, B. C. Byrnes, and H. G. Thomasson.

J. H. Nelson, *Chairman*
Committee of Tellers

Appendix 4—Report of Committee on Geophysical Abstracting

JOHN LYMAN, Chairman
WERNER A. BAUM JOHN C. REED
J. W. JOYCE ARTHUR H. WAYNICK

This Committee was established at the Executive Committee meeting of May 4, 1958 [*Trans.*, Aug. 1958, p. 758] to study the problem of implementing the abstracting and indexing of geophysical items. At the same meeting a motion was adopted favoring the objective of a complete geophysical abstract journal "without financial encroachment upon the regular funds of the Union."

In pursuing these objectives, the Committee has met at intervals during the summer, as far as the varied activities of its members permitted. It has learned of several projects to abstract or index geophysical items.

One is an *International Journal of Geological Abstracts* of the International Geological Congress. As currently envisioned, this journal would not cover magnetism, aeronomy, or geodesy. The prospects that it will actually commence in 1959 look slim.

Another is the *Geological Abstracts*, which the Geological Society of America is currently transferring to the American Geological Institute. This journal reproduces only authors' abstracts, and cannot be regarded as anything like a complete coverage of the field, especially outside of North American geology.

Geophysical Abstracts of the U. S. Geological Survey will be continued only until some outside agency fills the gap. It produces only about 1400 abstracts annually, far short of the estimated 8500 items that appear in the field.

Meteorological Abstracts of the American Meteorological Society prints 6000 abstracts a year in meteorology, hydrology, glaciology, oceanography, and upper atmosphere. With about 40 per cent increase in its size it could cover the entire geophysical field. We have had correspondence with the American Meteorological Society concerning a proposal to expand *Meteorological Abstracts* into such coverage of the entire field of geophysics.

This Committee, having compared the propositions described above, with the possibility of initiating a new geophysical abstract journal entirely under the auspices of the Union, feels that, in view of the manifold problems connected with the launching at this time of the monthly *Journal of Geophysical Research* and the continuation of the *Izvestiia* translation, it would be more prudent to encourage one of the other projects mentioned than for the Union to undertake an entirely independent operation. Among those listed above, the *Meteorological Abstracts* proposal appears to have the greatest merit by a very wide margin. The Committee therefore recommends that the proposal of the American Meteorological Society be endorsed by the American Geophysical Union and that a permanent committee of the Union be established to work with the American Meteorological Society on the further implementation of the basic objective.

Report on the Thirteenth Annual National Conference on Educational and Professional Standards

Note: This Conference was held at Bowling Green State University, Bowling Green, Ohio, June 24–28, 1958, under the auspices of the National Education Association. AGU's representatives were John R. Coash, Professor of Geology at Bowling Green State University; Paul M. Pepper, Assistant to the Director, Ohio State University Research Foundation; Howard J. Pincus, Professor of Geology, Ohio State University; and C. Warren Thornthwaite, Director, Laboratory of Climatology, Elmer, New Jersey. The following is a summary report prepared by Coash.

The members of the AGU delegation were in attendance at various sessions of the conference and so varying reports were received to some extent. Being at home here in Bowling Green, I was personally able to attend most of the sessions. As is the usual pattern at these education meetings, there were general sessions with speakers followed by discussion groups. The speakers aired a number of views from both sides of the fence, that is, the scholar and the professional educator. The groups then pursued, on successive days, these topics: Purposes of Education, Subject Matter Preparation, and Professional Preparation. Summaries of the discussion (by 30–40 groups of perhaps 25 people each) were then presented.

The following comments and recommendations, while not those of the entire AGU delegation, were made by one or more of our delegates, either at the conference or in more recent correspondence. The order of presentation has no significance.

(1) AGU (and other Earth Science professional organizations) should have some sort of policy to guide future delegations. It is time for constructive comments on education, on the school, and on the responsibilities or our profession.

(2) Now that the door has opened, there will probably be more meetings of this type. Cooperative meetings in many states are already planned. AGU should be ready to participate.

(3) We are informed that Earth Scientists appointed to National Committees were lax. We know that many Earth Scientists are generally lax or disinterested in promoting Earth Science in school curricula. We do not favor this viewpoint. What is more basic or more interesting to a youngster than this natural world? My own discussion group at the conference (and every other similar local group I have been in during the past several years) agreed vigorously that the natural sciences—Earth Science and Biological Science—should be fundamental, especially in the elementary school curriculum.

(4) We were disappointed to see so little time at the conference devoted to subject-matter preparation.

(5) However, the joint conference was a good idea.

We were all impressed with the idea that the professional educators were recognizing once more the importance of competence in subject matter. In at least one discussion group this was entirely agreed upon, even at the elementary level. This is surely gratifying.

(6) Funds, especially for salaries, are still our biggest drawback to education and to teacher preparation.

(7) Subject matter people should have more, and more clearly defined, authority in certifying and in setting up certification requests.

(8) Science courses, with graduate credit in education for the teacher, are badly needed. Here the Earth Scientists and AGU could offer something constructive.

(9) AGU could help by circulating or reprinting in part things such as *Education in Review* from the New York Times of July 6, 1958 and the AAAS report in progress on *Recommendations for the Preparation of High School Teachers of Science and Mathematics*.

(10) Most of the delegates felt that most everyone at the conference wanted the same things. Differences were slight and represented background rather than goals.

We most heartily endorse further participation in such conferences. Perhaps we ought to sponsor some of our own.

JOHN R. COASH, *Chairman*

Annual Meeting of the Geophysical Society of Hawaii

The Geophysical Society of Hawaii, serving as the Mid-Pacific Regional Branch of the AGU, held its annual meeting on September 30 and elected the following officers: President, Gordon Macdonald; Vice President, Nicholas Chavasse; Secretary-Treasurer, Saul Price; and Councilor, Walter Steiger. Thomas S. Austin is the retiring President. Colin Ramage's term as councilor continues for another year.

Special Announcements

List of Official Nominees for Officers of the Union, of the Sections, and of Two of the Regional Committees for the Triennium July 1, 1959 to June 30, 1962

Union or Section	President	Vice President	Secretary[a]
Union	Lloyd V. Berkner	F. W. Reichelderfer George P. Woollard	A. Nelson Sayre John Lyman
Geodesy	Charles Pierce	Floyd W. Hough	Buford K. Meade
Seismology	L. M. Murphy	J. A. Peoples, Jr.	B. F. Howell, Jr.
Meteorology	Thomas F. Malone B. Haurwitz	Gordon E. Dunn E. W. Hewson	Woodrow C. Jacobs
Geomagnetism and Aeronomy	Leroy R. Alldredge	C. T. Elvey	J. Hugh Nelson
Oceanography	John Lyman Walter H. Munk	Arnold Arons D. W. Pritchard	Eugene C. La Fond Dale Leipper
Volcanology, Geochemistry, and Petrology	Alfred O. C. Nier	Francis J. Turner	Irving W. Friedman
Hydrology	Harry F. Blaney Walter B. Langbein	Wm. C. Ackerman Wm. E. Hiatt	Ralph N. Wilson Charles C. McDonald
Tectonophysics[b]	Patrick M. Hurley	L. B. Slichter	H. Richard Gault

[a] For General Secretary in the case of the Union.

[b] Two members of the Executive Committee of the Section are to be elected also. The nominees are Clarence R. Allen and Iris Borg.

Nominees for Regional Committees (nine to be elected)

Pacific Southwest Regional Committee (Arizona, California, and Nevada)
Hydrology: Arthur F. Pillsbury, Joseph F. Poland, and David K. Todd
Oceanography: Henry W. Menard and Jacob B. Wickham
Meteorology: W. D. Duthie, Eugene Bollay, and Robert E. Holzer
Geomagnetism and Aeronomy: E. H. Vestine

Pacific Northwest Regional Committee (Idaho, Montana, Oregon, Washington, and Wyoming)

Geodesy (one to be elected): Donald J. Brown and Ector B. Latham

Seismology and *Tectonophysics* (one to be elected): Mark F. Meier and Peter Misch

Meteorology (two to be elected): Lenard Bissell, Carlton Jencks, Donald W. Kuehl, and Melvin J. Ord

Geomagnetism and Aeronomy, and *Volcanology, Geochemistry, and Petrology* (one to be elected): Keith E. Anderson and Peter B. Boyer

Oceanography (one to be elected): Ned Bethlahmy and Wayne V. Burt

Hydrology (three to be elected): Charles L. Barker, Thomas H. Campbell, Harold D. Hafterson, Albert M. Moore, Calvin C. Warnick, and R. A. Work

North Central Regional Committee (Minnesota, Iowa, Missouri, North and South Dakota, Nebraska, Kansas, and contiguous Canadian provinces)

Harry C. Bolon, Martin E. Nelson, Robert J. Pafford, Robert H. Shaw, Athelstan Spilhaus (other nominations pending)

Explanatory note—In accordance with the Statutes and By-Laws as amended, elections by mail ballot are to be held in the first part of 1959. The Committees on Nominations for the Union and the Sections were appointed as follows, with the first-named as Chairman: **Union,** L. H. Adams, Walter H. Bucher, and M. A. Tuve; **Geodesy,** A. J. Hoskinson, Gunnar Leifson, and Julius Speert; **Seismology,** Beno Gutenberg, J. E. Oliver, and Don Tocher; **Meteorology,** Sigmund Fritz, John C. Freeman, and C. L. Hosler; **Geomagnetism and Aeronomy,** J. W. Joyce, Walter M. Elsasser, Carl W. Gartlein, J. P. Heppner, and E. H. Vestine; **Oceanography,** D. E. Carritt, R. S. Arthur, B. C. Heezen, R. C. Vetter, and W. S. Von Arx; **Volcanology, Geochemistry, and Petrology,** W. W. Rubey, George R. Tilton, and O. F. Tuttle; **Hydrology,** Harold G. Wilm, Arthur Johnson, and F. J. Veihmeyer; **Tectonophysics,** Ernst Cloos, M. King Hubbert, and L. L. Nettleton; **Pacific Southwest Region,** V. A. Vanoni, Eugene Bollay, and Robert E. Holzer; **Pacific Northwest Region,** Hollis M. Orem, David Rockwood, and Robert T. Beaumont; North Central Region, Phillip Light, Carl Kisslinger, and LeRoy Scharon.

The Executive Committee of the Union has established procedures for nomination and election of officers of the Union, as published in the December 1946 issue of the *Transactions*, page 910. These are as follows: (1) Nominations shall be initiated by a small Nominating Committee consisting of three or five members, appointed by the President. (2) At least two persons shall be nominated for each of the offices of President, Vice President, and General Secretary. (Rule suspended for the elections of 1959 by action of the Executive Committee by mail ballot in July, 1958, to give the Committee on Nominations discretion as to the number of nominees it may submit for any office.) (3) Such nominations shall then be submitted by the Nominating Committee to the Executive Committee, which body may accept the report, or add other nominees for such offices. If there are other nominees, it will then proceed to select by secret ballot not less than two official nominees for each office. (4) Such nominations shall then be announced to the membership, sufficient time being provided before election to permit further nominations by petition when signed by one per cent (51 at present) of entire membership, it being mandatory that nominations by petition be added to the official nominations (see (9), below). Ballots containing official nominees and those submitted by petition shall be mailed to the active membership and such ballots, postmarked before a specified date, shall be marked and forwarded by the membership to the General Secretary. (6) The General Secretary within ten days after the specified date shall turn over all such ballots for tallying to a Committee of Tellers consisting of one member selected from each of the eight Sections and one member from the Executive Committee. (7) The Committee of Tellers shall make report to the General Secretary within ten days, showing the result of the ballot. (8) A plurality of votes cast shall elect. (9) Consent of each candidate is to be obtained before placing his name on the ballot. (10) The Sections shall be urged to adopt similar procedures.

Similar Section procedures were established and were published in the *Transactions* of December 1946, with amendments covering Seismology and Hydrology in the *Transactions* of August 1949, page 627. In the summer of 1952, the Executive Committee of the Section of Geodesy voted to permit the nomination of but one candidate for each office of that Section, and at the annual meeting of May, 1958, the Section of Tectonophysics took a like step. The procedures will not be repeated in full here. All provide for nominations by petition, the number of member petitioners affiliated with the Section being as follows: Geodesy, ten members; Seismology, 13 members; Meteorology, 25 members; Geomagnetism and Aeronomy, one per cent of those affiliated with the Section (12 members at present); Oceanography, ten members; Volcanology, one per cent of those affiliated with the Section (nine members at present); Hydrology, 25 members; and Tectonophysics, 15 members.

Please note that nominations by petition must include written consent from the nominee, to be transmitted to the office of AGU with the petition.

The following schedule for nominations and elections has been established:

By November 10, 1958, steps (1) to (3) and step (9) of procedure must be complete for the official nominees.

In Transactions of December, 1958, publish list of official nominees with explanatory note.

By February 1, 1959, nominations by petition must be in the office of AGU with written consent of nominees.

By March 1, 1959, ballots carrying names of official and petition nominees, will be mailed to the membership. A brief biographical sketch relating to each nominee will accompany, but not be a part of, the ballot.

On March 31, 1959, balloting will close. Ballots must be postmarked not later than that date and be received in the office of AGU not later than April 4, 1959, in order to be counted.

By April 10, 1959, ballots will be turned over to the Committee of Tellers.

By April 20, 1959, results of tally will be turned over to the General Secretary, results to be announced at the Annual Meeting May 4–6, 1959, and published in the *Transactions* in June, 1959.

In addition to the election of Union and Section officers, two Regional Branches will hold elections by mail ballot, the nominees to be voted upon only by members in those Regions. The names are also shown in the accompanying table.

Waldo E. Smith, *Executive Secretary*

WALTER M. ELSASSER NAMED TWENTY-FIRST WILLIAM BOWIE MEDALIST—Walter M. Elsasser, Professor at the Scripps Institution of Oceanography of the University of California, has been named at the recent Executive Committee meeting as the Twenty-First William Bowie Medalist in recognition of his outstanding work in the theoretical aspects of geophysics and especially in the field of magnetohydrodynamics. The award will be made at the time of the Fortieth Annual Meeting of the AGU in Washington next May.

PACIFIC SOUTHWEST REGIONAL MEETING AT STANFORD, February 5–6, 1959—Plans for this meeting are now well along. Interested persons should get into touch with the Chairman of the Regional Committee, Vito A. Vanoni (California Institute of Technology, Pasadena 4, California), or with Joseph B. Franzini (Civil Engineering Department, Stanford University, Stanford, California), Chairman of the Program Committee.

FORTIETH ANNUAL MEETING TO BE HELD IN WASHINGTON, D. C., May 4–7, 1959—Your attention is invited to the extended announcement concerning this meeting on pages 993–994 of the October issue of the *Transactions*. Note that titles and abstracts of papers for the programs should be sent in as soon as possible to the appropriate persons and that in general the closing date is February 20, 1959, except for Meteorology for which the closing date is January 20, 1959.

Abstracts must be informative and concise, and not more than 150 words (see Suggestions to Authors in the *Transactions* of April 1957, p. 285, for ideas regarding abstracts).

Standard-size slide projectors (3¼ × 4 inches) will normally be available at the meeting, but other facilities will be provided only if especially requested well in advance. Persons inexperienced in the proper preparation of figures and tables for the making of slides should write to the AGU office requesting information on this. One general rule, however, is to avoid crowding and attempting to show too much on one slide. More than two or three curves on one slide tend to be confusing. Large-sized lettering is essential.

An advanced copy of the paper is requested for use by science writers and the press. Please send in by April 15, 1959. It is discouraging to have to tell a reporter inquiring about a certain paper, "That one hasn't come in."

In case the paper is being submitted for publication in the *Journal of Geophysical Research*, complete manuscripts, double-spaced, in triplicate, with figures and tables should be sent to Dr. James A. Peoples, Jr. (Department of Geology, University of Kansas, Lawrence, Kansas) noting that the paper is to be presented at the combing meeting.

The Section on Meteorology is to meet jointly with the American Meteorological Society. Commander Max A. Eaton (CNO (Op-583), Navy Department, Washington 25, D. C.) is Chairman for the joint program and material relating to the program should be sent directly to him. On this committee also are: F. W. Burnett, H. A. Bedient, A. W. Bostick, and H. V. Goodyear. The meeting in Meteorology will extend to May 7. Contributions in the following areas will be welcomed: cloud physics, synoptic meteorology, recent developments in forecasting and practice including utilization of numerical products, and meteorological instrumentation.

Block bookings have been made at three hotels as follows:

Roger Smith Hotel, Pennsylvania Ave. at 18th St., N.W.
Willard Hotel, Pennsylvania Ave. at 14th St., N.W.
Raleigh Hotel, Pennsylvania Ave. at 12th St., N.W.

Make your room reservation early directly with the hotel of your choice, citing the AGU block booking if you write to one of the three hotels noted.

PLANS FOR THE TWELFTH GENERAL ASSEMBLY OF IUGG—As previously announced, the Twelfth General Assembly of the International Union of Geodesy and Geophysics will be held in Helsinki, Finland, July 25–August 9, 1960. The following Committee has been designated by Finland's National Committee for Geodesy and Geophysics: President, W. A. Heiskanen; Vice President, Vilho Väisälä; Secretaries, Pentti Kalaja and T. J. Kukkamäki. Other members are R. A. Hirvonen (for the Association of Geodesy), Eijo Vesanen (for the Association of Seismology and Physics of the Earth's Interior), Matti Franssila (for the Association of Meteorology and Atmospheric Physics), Christian Sucksdorff (for the Association of Geomagnetism and Aeronomy), Ilmo Hela (for the Association of Physical Oceanography), Allan Sirén (for the Association of Scientific Hydrology), and Vladi Marmo (for the Association of Volcanology).

While citizens of the United States should make known their plans to attend and for participation through the U. S. National Committee (that is, the American Geophysical Union), other questions may be addressed to Secretary Pentti Kalaja, Finnish Geodetic Institute, Itämerenk 51, Helsinki, Finland.

PLANS FOR THE ENGLISH EDITION OF *Izvestiia*, GEOPHYSICS SERIES—*Bulletin* (*Izvestiia*), *Geophysics Series*, of the Academy of Sciencies, USSR, will be published in an English edition directly by the AGU for the calendar year 1959, according to present plans. Subscriptions ($25.00 for the 12 numbers to be issued during 1958) with payment should be sent direct to the American Geophysical Union. *Izvestiia* for 1957 is being produced by Pergamon Press under arrangements with the American Geophysical Union. Subscriptions for that year and purchases of back numbers for 1957 should still be sent to the Pergamon Press, 122 East 55th Street, New York 22, New York.

NATIONAL ACADEMY OF SCIENCES

Number 17 • November 1958

IGY BULLETIN

A monthly survey by the U. S. National Committee for the International Geophysical Year. Established by and part of the National Academy of Sciences, the Committee is responsible for the U. S. International Geophysical Year program in which several hundred American scientists are participating and many public and private institutions are cooperating.

Status of Geomagnetism Program

The following material is based primarily on a report to the US National Committee for the IGY by Elliot B. Roberts, Chief, Division of Geophysics, US Coast and Geodetic Survey, and Vice-Chairman, USNC-IGY Technical Panel on Geomagnetism.

The major portion of the earth's magnetic field is thought to be generated by electric currents within the earth. The remaining portion, about 5% of the field, is generated externally, it is believed, by great, globe-girdling systems of electric currents in the charged, or ionized, regions of the upper atmosphere. The earth-generated part of the field is relatively stable, undergoing slow, "secular" changes measured in years, tens of years, or even centuries. The externally-generated part of the field is characterized by rapid, or transient, fluctuations measured in days, hours, minutes, and seconds. It is with these transient fluctuations that the IGY Geomagnetic Program is mainly concerned.

Daily variations in the magnetic field are believed to be tidal (solar and lunar) in origin. Other rapid fluctuations and disturbances may result from the entry into the earth's upper atmosphere of (1) energetic ionizing radiations, and (2) high-velocity, electrically-neutral streams of corpuscles. Both the radiations and the corpuscles originate in explosive activity on the sun.

The magnetic-field vector (magnitude and direction) at any point is measured in terms of various elements or components. These include the magnetic intensity in the vertical and horizontal planes, dip (inclination of the magnetic vector with respect to the horizontal), and declination (the angle between the magnetic vector and the geographic meridian).

Continuous recording of the magnetic field components is accomplished with instruments called magnetometers or magnetographs. Absolute calibration must be applied to these instruments periodically with specially-designed magnetometers. At stations where observations are made over many years, permitting study of the secular changes, observatory-type instruments are employed. These are magnetometers characterized by low, uniform base-line drift and stable response. At stations established for short periods, where recording of magnetic-field variations and storm responses is of major interest, small portable magnetometers called variometers or variographs are used. Absolute calibrations are also applied to variometers, but in general the records are more useful for study of transient rather than secular changes.

The several components of the magnetic field have for years been measured and recorded by instruments installed at magnetic observatories in many parts of the world. These have helped form a picture of the overall magnetic field. During the IGY, however, networks of stations have been established in regions of special interest. Examination of the differences between records obtained at the stations reveals information on the behavior, location, and extent of the electric currents circulating in the upper atmosphere.

The objective of the geomagnetism program, broadly speaking, is to record synoptically the variations in the earth's magnetic field. The frequency band primarily under study ranges from about 50 cycles/sec to one cycle/yr. Geographic areas of greatest interest are the polar regions, including the auroral zones, and the rather narrow band along the magnetic equator. Figure 1 shows the locations of IGY geomagnetic stations in equatorial and middle latitudes as well as some in high latitudes (see *Bulletin No. 3* for map showing all polar stations).

Polar Regions

Records obtained at the magnetic observatories at the Little America, Byrd, Wilkes, and South Pole IGY Stations, Antarctica, furnish material for the study of magnetic storm conditions as a world-wide phenomenon—allowing comparison with records obtained in the equatorial and north polar regions.

The variometer on IGY Drifting Station A, in the Arctic Ocean ice pack about 300 mi from the North Pole, supplies information on general magnetic activity well within the auroral zone. Rotation, tilt, and drift of the station make necessary elaborate computations to reduce the records to standard components. Therefore, no routine reductions are contemplated.

Continental US

Records received from the east-west network of variometer stations in the United States are available for study of the effects of mass-transport of ionized gases or of other meteorological relations. At present, processing of the records consists only of tabulating mean hourly values.

South American Network

Near the magnetic equator, the daily variation in the horizontal component of the earth's magnetic field is unusually large. This abnormality is exceptionally well exhibited at Huancayo, Peru, where a permanent magnetic observatory is located very close to the magnetic equator.

In 1949, observations were made at fourteen locations along the west coast of South America, from geographic latitude 3.4° N to 16.2° S, to study this variation. These observations showed a steep decrease in the amplitude of the daily fluctuations of the horizontal component with distance north and south of the equator. This indicated the existence of a narrow band of concentrated electric current flowing eastward in the upper atmosphere during midday. This current—the equatorial "electrojet"—is superposed on the more diffuse current distribution that accounts for the normal, quiet-day magnetic variations.

To determine whether magnetic field variations other than the daily variation also show electrojet effects, four stations equipped with Askania variographs were established for the IGY on the west coast of Peru by the Department of Terrestrial Magnetism, Carnegie Institution of Washington, in cooperation with the Instituto Geofisico de Huancayo. They are located at Talara, Chiclayo, Chimbote, and Yauca, ranging from geographic latitude 4° N to 15° S. Magnetographs at the Instituto Geofisico de Huancayo (12° S) provide data at a fifth location and a magnetograph recently installed at the University of Arequipa (17° S) will provide data at a sixth.

To locate the latitudinal limits of electrojet effects on the daily magnetic variation, and to determine strategic locations for the four Askania variograph stations mentioned above, records were obtained at 16 more-or-less uniformly spaced locations between the geographic equator and 22° S in the spring of 1957. Two or three complete daily records were secured at each station.

The maximum daily variation of the

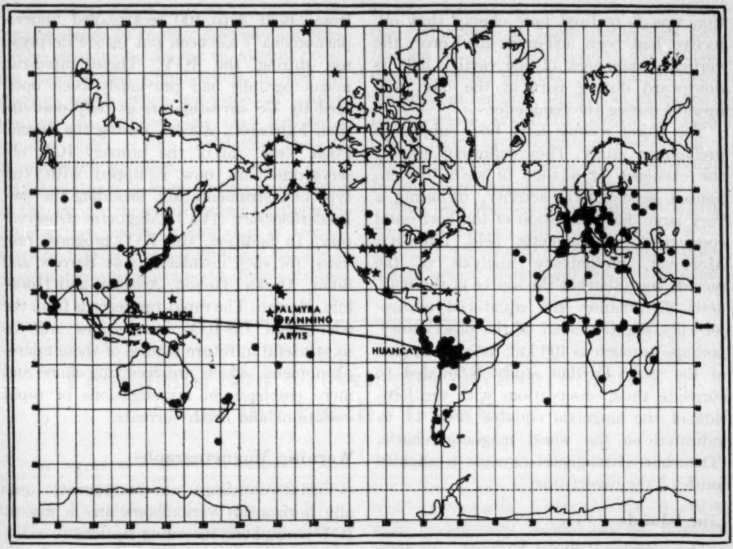

Fig. 1. *IGY Geomagnetic Stations. Stars: US Stations. Dots: Stations of other countries. Circled Stars: Cooperative Stations. Heavy solid line represents approximate position of magnetic equator.*

horizontal component was found to occur within 1° of latitude of Huancayo (12° S). This is in accord with results from the 1949 survey. It is also confirmed by the fact that the daily variation of the vertical component of the earth's magnetic field, obtained during the 1957 survey, changes sign at a latitude within 1° of Huancayo. A maximum daily variation in the vertical component occurred at about 16° S, and another maximum, with opposite sign, occurred near 8° or 9° S.

The north-south distance of 500 mi between these extremes provides a rough estimate of the width of the electrojet band. The difference with latitude of the daily variation of the vertical component indicates the importance of the return currents, which must flow westward, to the north and south of the eastward-flowing electrojet.

To estimate reliably the height and width of the electrojet, the electric current system of the electrojet field must first be derived. Before this derivation can be accomplished, the normal, quiet-day solar variation, estimated from data obtained at locations free from the influence of the electrojet, must be subtracted. Such height and width estimates have not yet been completed.

A preliminary examination of records indicates that many of the vertical-component fluctuations related to solar disturbances are greatest at the same latitudes where the largest quiet-day solar tidal variation in this component was observed. The sign of the fluctuations is opposite at these two latitudes, indicating electrojet effects.

Pacific

The site for the Koror Observatory, in the Palau Islands, was chosen with the intention of establishing a recording station as near as possible to the magnetic equator. Not until the observatory was actually in operation was it realized how closely that objective had been achieved: at Koror, the vertical component of the earth's field is downward during part of the day, and upward during the remainder.

The Koror records have been subject to preliminary study. They definitely support the existence of a zone of markedly enhanced geomagnetic activity, including a very large daily variation of the horizontal component of magnetic field intensity. Moreover, preliminary analysis of the records suggests that the source of the magnetic disturbance—the equatorial electrojet—lies slightly north of the observatory, perhaps as much as 100 km, for at least part of the year. Further study is needed to correlate these observations with the location of the magnetic equator (Fig. 1), as indicated on the world magnetic charts. (The charted magnetic equator is slightly south of the observatory.)

Line Islands

The Jarvis-Palmyra-Fanning project, operated by Scripps Institution of Oceanography with instruments supplied by the US Coast and Geodetic Survey, began operation very shortly after the formal commencement of the IGY.

Records from the three stations were shipped to the C&GS late in May 1958 for delivery to World Data Center A. Although there has been no opportunity to examine them critically, a preliminary inspection shows that the records tend to support observations made elsewhere of a concentration of electrojet effects in the vicinity of the magnetic equator. Such effects are indicated by the increased daily variation and by disturbance effects evident in the Jarvis records as compared with those from the more distant members of the group.

Rapid-Run Records

A type of instrumentation badly needed at US Magnetic Observatories for many years—instrumentation for recording rapid fluctuations of the earth's field in the range from about 4 to 100 secs (called "microphenomena") has been put into widespread use during the IGY. These rapid-run magnetographs had previously been operated by US investigators at only one station, Fairbanks, Alaska, during the Second Polar Year. All of the primary IGY observatories are now equipped with this type of instrumentation, including the new Fredericksburg (Va.) Magnetic Observatory. In addition, the IGY program provided for such installations at Barrow and Sitka, Alaska, Tucson, Arizona, and Honolulu, Hawaii. The rapid-run records from the widespread US-IGY installations will be most useful in future studies of these microphenomena, which are receiving more and more emphasis in investigations of rapid variations and earth currents.

Warning Magnetographs

Visible-recording, one-component (usually horizontal) variometers are in use at IGY ionospheric recording stations to assist in correlating ionospheric observations with the general level of magnetic activity. The records will not be systematically archived in the World Data Center.

Sub-Audio Project

The sub-audio frequency project was set up to provide a description, using magnetic tape recordings, of geomagnetic fluctuations in the frequency range of 1 to 50 cycles/sec.

The program involves investigation of the nature of sub-audio frequency signals which precede magnetic disturbances in the auroral zone by about a day. These signals may be confused with fluctuations originating in thunderstorm activity at lower latitudes. Hence, careful analysis is necessary. The most conclusive evidence will come from statistical analysis of the signal level as a function of frequency and time. Differences in signal levels between the vertical and horizontal components of the earth's field will also aid in this differentiation. Preliminary examination of the visual record of the overall signal level, at the time of recording, tends to confirm previous findings.

The records also appear to confirm previous reports that signal levels in this frequency range, when recorded at appropriately situated stations, can furnish a running index of the world-wide level of thunderstorm activity.

Observations of some of the wave forms of the signals show interesting phenomena. Among these is the appearance of oscillations or regular micro-pulsations. Signals of varying frequency also occur. Some of them at first decrease in frequency, resembling the "whistlers" of audio frequencies (see *Bulletin No. 6*). Then, however, they sometimes increase; whistler propagation could not account for this. Analysis of these wave forms—which, at such frequencies, probably result from hydromagnetic phenomena—should provide new data on the sub-audio frequency geomagnetic fluctuations.

Five field stations participate in the program—at Ramey Air Force Base, Puerto Rico; Ft. Devens, Mass.; Mt. Evans, Colorado; College, Alaska; and Thule, Greenland.

Pendulum and Gravimeter Measurements of the Earth's Gravity

This report is based upon material furnished by George P. Woollard, Department of Geology, University of Wisconsin.

The mass of the earth exerts an attractive force—gravity—on all bodies on the earth. However, because the earth is not a perfect sphere, because its mass is not uniformly distributed, and because the centrifugal force resulting from its rotation varies with latitude, gravity is not the same all over the earth. Measurement of the differences in gravity from place to place therefore reveals much information about the physical characteristics of the earth. Such measurements are especially important in studies of the true shape of the earth and the thickness and mass of its crust; in location of underground ore bodies and undersea mountains; and in accurately determining elevations and distances on the earth's surface.

The major aims of the IGY Gravity Program are to expand existing gravity networks in an effort to achieve as complete global coverage as possible, and to increase the reliability of gravity measurements. In the US program, scientists of the University of Wisconsin, under the direction of George P. Woollard, are making gravity determinations throughout the world using pendulums and gravimeters. Although less sensitive than gravimeters, pendulums can measure reliably changes in the gravity field of the earth. Hence, they are being used to establish a number of accurate key points to serve as linkages between the gravity networks of many countries and as a standard for calibrating the more sensitive gravimeters. Similar key points which existed prior to the IGY are being recalibrated. Within this framework, gravimeters are able to make highly sensitive measurements of the variations in gravity from one point to another.

A. PENDULUM PROGRAM

The IGY pendulum program is a continuation of one that has been under way at the University of Wisconsin since 1951. Early measurements revealed systematic and random errors in accepted gravity base values. These errors were too large to permit effective integration of the world's gravity data into a unified whole having an overall accuracy approaching the desired value of 1 milligal. (One milligal, or mgal,

Table 1. *Comparison of Gulf and Cambridge Pendulum Values in North America*

Location	Cambridge	Gulf	Difference
Fairbanks, Alaska	982.2477	.2455	−2.2
Whitehorse, Y. T.	981.4073	.7487	−1.6
Fort St. John, B. C.	981.4073	.4054	−1.9
Grand Prairie, Alb.	981.3195	.3176	−1.9
Edmonton, Alb.	981.1691	.1681	−1.0
Red Deer, Alb.	980.9988	.9970	−1.8
Lethbridge, Alb.	980.7612	.7590	−2.2
Ottawa, Ont.	980.6220	.6206	−1.4
Huron, S. D.	980.4555	.4535	−2.0
Madison, Wis.	980.3696	.3688	−0.8
Washington, D. C.	980.1193	.1192	−0.1
Beloit, Kans.	980.9990	.9985	−0.5
Tulsa, Okla.	979.7664	.7665	0.1
Houston, Texas	979.2990	.2983	−0.7
Monterrey, N. L.	978.8055	.8049	−0.6
Mexico City, D. F.	977.9415	.9419	0.4

equals $1/1000$ gal, which represents an acceleration of 1 cm/sec.^{2}) Actually, apparent errors of over 20 mgals were discovered. The Gulf compound quartz pendulum apparatus was chosen to establish a series of world standardization measurements as it appears to hold the greatest promise for obtaining accurate values of gravity throughout the world.

Description of Apparatus

The Gulf pendulums are designed to minimize knife-edge wear effects at the point of suspension, and the pendulum case is ionized with a radioactive salt to dissipate electrostatic charges built up on the moving pendulums. The pendulums are operated at constant temperature and are kept sealed in a dry atmosphere. The use of two pendulums swinging 180° out of phase on a common support minimizes sway in the support. Timing is done with a crystal-regulated chronometer periodically checked against WWV radio time signals. Recording was first done photographically, but now the period is read directly from an electronic digital recorder.

Observation Procedure

An observation consists of four independent pendulum measurements of one hour's duration each. The four measurements are made to eliminate errors that result because the pendulum knife edge is positioned slightly differently on the bearing flats during each measurement. When variations between independent swings are greater than ±0.2 mgal, observations are continued until four agree within this arbitrary limit. The mean value for all swings is adopted as the period for the site.

To guard against error, two precautions are now being taken that were not followed earlier. One is to repeat in reverse order any series of observations. For example, the series Panama, Quito, Lima, La Paz, Santiago would be repeated from Santiago back to Panama. The other is to use a geodetic gravimeter in conjunction with the pendulum observations. Thus, if there are any jumps owing to knife-edge wear, or to any other cause, there is a double check to indicate where and when trouble occurred and how much of an error was introduced. Since this procedure was adopted, with the beginning of the IGY program, there have been no problems concerning values. This does not apply to earlier measurements, some of which were doubtful and required repeat observations.

Accuracy of Values

Studies involving three different sets of pendulums have been conducted, and while a single set of pendulums is inherently consistent to ±0.2 mgal, one set may differ from another by as much as 1.0 and occasionally 1.5 mgal on an interval measurement.

In addition, comparative measurements have been made against the magnetically compensated compound Invar pendulum of Cambridge University, England, and the magnetically compensated single Invar pendulum apparatus of the US Coast and Geodetic Survey. Such comparisons show no systematic differences; overall agreement within 1 mgal was obtained between Alaska and Mexico (see Table 1).

Another independent evaluation of the pendulum results is furnished by comparative measurements with carefully calibrated, high-range, geodetic-type gravimeters having a reading accuracy of 0.1 mgal. Here, the average agreement is found to be about ±0.5 mgal (see Table 2).

On the basis of all of these comparative measurements, it appears that an accuracy of about 0.3 to 0.5 mgal is being obtained with the Gulf pendulums.

Program of Observations

Prior to the IGY, one series of pendulum measurements from Mexico City to Fairbanks, Alaska, had been completed, covering a range of approximately 4800 mgals. This series was adopted as a standard for determining the operating characteristics and calibration of high-range geodetic gravimeters used by the University of Wisconsin for global gravimeter measurements. To strengthen these standardization measurements, the Dominion Observatory of Canada, using the Cambridge pendulums, and the USC&GS reoccupied most of the University of Wisconsin sites. On the basis of the agreement obtained, it was decided to extend the pendulum program and establish another, comparable standardization range for other parts of the world. At the same time, this would serve as a control net of bases for integrating gravity data from all sources into a unified system. This second series of Gulf pendulum bases was established just prior to the IGY. It extends from Oslo, Norway, to Cape Town, South Africa. At most of the sites occupied, observations have also been made with the Cambridge pendulums.

A problem in gravity work is the use of several different gravity calibration standards in different parts of the world. These differ by as much as 12 mgals per 1000 mgals of change in gravity. As this situation leads to major discrepancies that would hamper attempts to integrate world data, it was decided that additional Gulf and Cambridge pendulum measurements were desirable. These were included in the IGY Program.

Results

The program to date has resulted in a new series of Gulf pendulum measurements which extends the North America standardization range northward to Pt. Barrow, Alaska, on the Arctic Ocean, and southward through Panama to Punta Arenas, Chile, at the southern tip of South America. Figure 2 shows the geographic distribution of Gulf pendulum sites. In the Pacific Ocean area, measurements have been established

Table 2. *Comparisons of Gravimeter and Gulf Pendulum Values in the United States*

Location	Av. M-K Pendulum Value	Gravimeter Values		Difference from Pendulum Values (mgals)	
		W10F	147	W10F	147
Cutbank, Mont.	980.6077	980.6084	980.6083	+0.7	+0.6
Great Falls, Mont.	980.5263	980.5269	980.5269	+0.6	+0.6
Huron, S. D.	980.4535	980.4533	980.4536	−0.2	+0.1
Billings, Mont.	980.3697	980.3704	980.3703	+0.7	+0.6
Madison, Wisconsin	980.3688	980.3689	980.3689	+0.1	+0.1
Sheridan, Wyo.	980.2254	980.2263	980.2265	+0.9	+1.1
Washington, D. C.	980.1007	980.1007	980.1007	0.0	0.0
San Francisco, Cal.	979.9863	979.9863	979.9864	0.0	+0.1
Casper, Wyo.	979.9550	979.9560	979.9557	+1.0	+0.7
Tulsa, Okla.	979.7665	979.7662	979.7662	−0.3	−0.3
Cheyenne, Wyo.	979.6990	979.7004	979.7000	+1.4	+1.0
Denver, Colo.	979.6103	979.6106	979.6104	+0.3	+0.1
Amarillo, Texas	979.4243	979.4237	979.4233	−0.6	−1.0
Houston, Texas	979.2983	979.2984	979.2984	+0.1	+0.1
San Antonio, Texas	979.1966	979.1975	979.1974	+0.9	+0.8
Laredo, Texas	979.0801	979.0806	979.0805	+0.5	+0.4

Note: W10F and 147 are two different Worden gravimeters.

along another north-south line—from the island of Hokkaido, Japan, southward through Australia and New Zealand to McMurdo Sound, Antarctica. Another meridional series of measurements is planned from northern Greenland southward to southern Argentina, and it is hoped to make some supplementary measurements in western Europe and Africa to round out the existing networks in these areas.

In addition, complementary measurements with the Cambridge pendulums have been made in Europe and Africa by B. C. Browne of Cambridge University, and measurements with these instruments are now in progress in South America.

B. GRAVIMETER PROGRAM

About ten years ago the first practical geodetic-type gravimeter was developed by S. P. Worden of Houston, Texas. This instrument has revolutionized the use of gravity measurements, not only for geodetic studies but also for many regional geophysical studies related to earth structure and geology. It overcame all of the major problems previously restricting long-range gravity connections. The instrument was small, light, rugged enough for field use, had a self-contained power source consisting of small dry-cell batteries, and had a reliable reading time of less than 5 min.

For the first time it was feasible to use commercial air transport for gravity measurements. Without special facilities and arrangements, a gravity reading could be made during the few minutes a plane was on the ground for a routine stop. A closed traverse of as much as 1000 mi could be completed within 12 to 14 hrs and a series of observations extending completely around the world in less than one week.

Although the Worden gravimeter is compensated for changes in temperature, it has an appreciable "drift" rate resulting from slow relaxation of the spring over a period

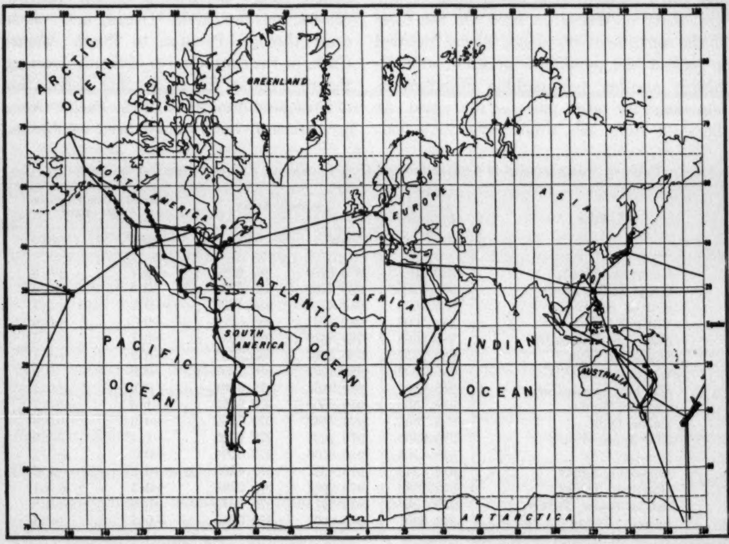

Fig. 2. *World Network of Pendulum Gravity Stations*

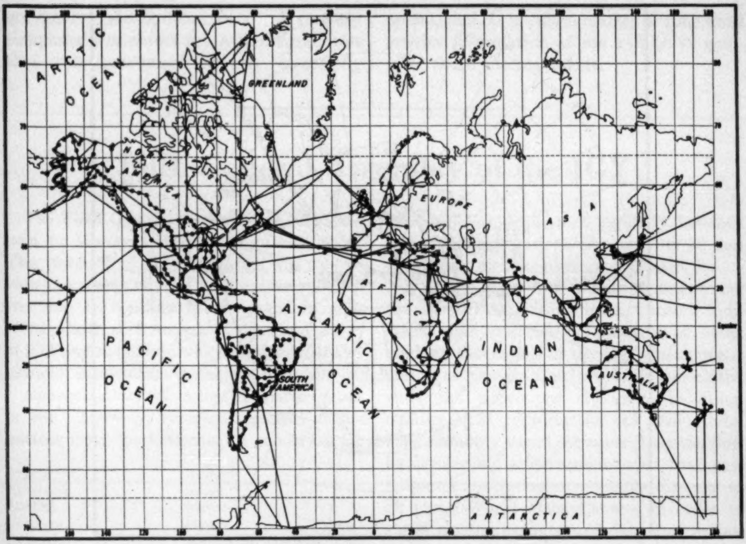

FIG. 3. *World Network of Gravimeter Stations*

of time. However, the speed with which the instrument can be used minimizes this drift effect. On the average, results reliable to 0.3 mgal can be obtained almost anywhere to which air transportation is readily available. The biggest problem in its use is that of calibration. (It was to resolve this problem that the program of gravity standardization measurements using Gulf pendulums was set up.)

How well these problems have been resolved is indicated by the comparison between pendulum gravity values and those for two Worden gravimeters having markedly different scale constants, sensitivity, and range values (Table 2).

Objectives of Program

The general objectives of the IGY gravimeter program, as in the pre-IGY period are: (1) to evaluate the accuracy of the various national gravity bases; (2) to integrate the national gravity bases into a unified network; (3) to extend and strengthen the international network of bases; and (4) to build up auxiliary gravity coverage on a regional basis in areas not likely to be investigated in the forseeable future.

Figure 3 shows the locations of the principal gravimeter bases, most of them at airports, throughout the world. Although a total of over 3000 bases have been established in 85 countries, large gaps still exist.

The IGY gravimeter program also includes establishment of base gravity values in Antarctica; traverse measurements in Antarctica; ice floe observations in the Arctic Ocean, with periodic ties to these stations from mainland bases; checking of key stations in the primary world network using the new, precise, "driftless," constant-temperature, LaCoste geodetic gravimeter; and expansion of the overall world net of gravity bases.

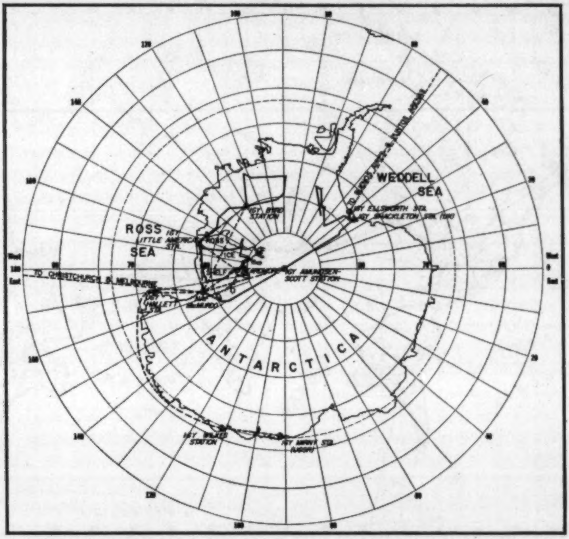
ROSS SEA
WEDDELL SEA
ANTARCTICA
IGY BYRD STATION
IGY LITTLE AMERICA STA.
ROSS ICE SHELF
IGY ELLSWORTH STA.
IGY SHACKLETON STA. (UK)
IGY AMUNDSEN-SCOTT STATION
TO CHRISTCHURCH & MELBOURNE
IGY HALLETT STA.
McMURDO
IGY WILKES STATION
IGY MIRNY STA. (USSR)
West
180
East
West
0
East

Fig. 4. *Gravity Stations and Lines Along Which US and British Gravity Measurements Have Been Made in Antarctica. Solid lines represent oversnow traverses; dashed lines represent ship or air routes.*

Antarctic Measurements

Figure 4 shows the locations of IGY gravity bases in Antarctica and routes along which gravity measurements were taken. The route of the British Commonwealth Trans-Antarctic traverse is also indicated since the gravity measurements on this traverse were made on a cooperative basis with an instrument provided by the University of Wisconsin.

Preliminary gravity values for the various Antarctic bases are listed in Table 3. Anomaly values (free-air) for the Byrd Station traverses average ±50 mgals from zero. These small anomalies suggest isostatic equilibrium, in which there is neither an excess nor a deficiency of crustal mass, thus implying crustal stability. The minor fluctuations, however, suggest considerable variation in the thickness of ice, the underlying rock types, or both. (The manner in which traverse gravity measurements have served to supplement the seismic measurements in determining the thickness of the ice cap is discussed in *Bulletin No. 13*.)

Table 3. *Antarctic Gravity Bases*

McMurdo	982.9923 gals
Little America	982.9820
Beardmore	983.0719
Pole	982.3290
Marie Byrd	982.5962
Hallett	982.7059
Wilkes	982.4000 (±.002)
Mirny	982.4020 (±.002)
Ellsworth	982.9279
Belgrano	982.9525
Shackelton	982.9397

Marine Measurements

One of the more significant phases of the US-IGY Gravity Program is the work being done by the Lamont Geological Laboratory in developing a workable shipboard adaptation of the Graf motion-compensated gravimeter (see *Bulletin No. 8*). A recently completed run across the Atlantic indicates that this instrument is now essentially operational. It is only a matter of time until gravity information at sea will be as complete as on the continents.

Fifth General Assembly of the IGY

The Fifth General Assembly of IGY was held in Moscow, July 30–August 9, 1958. The purpose of the Assembly was to review the status of IGY as it approached its end and to consider future needs in geophysics both with respect to the termination of IGY and to fields in which additional international cooperation appeared desirable.

Approximately 365 scientists participated in the Assembly, representing IGY committees from the following 35 countries:

Argentina
Australia
Austria
Belgium
Bulgaria
Burma
Canada
Chile
Czechoslovakia
Denmark
Finland
France
German Democratic Republic
German Federal Republic
Ghana
Hungary
India
Iran
Ireland
Israel
Italy
Japan
Mongolian Peoples Republic
Netherlands
New Zealand
Norway
Poland
Rumania
Sweden
Union of South Africa
Union of Soviet Socialist Republics
United Kingdom
United States
Viet Nam Democratic Republic
Yugoslavia

The Assembly was called by the Special Committee for the IGY (CSAGI). As at previous general assemblies, the meeting of CSAGI was characterized by working groups in the various IGY fields: world data centers, world days, meteorology, geomagnetism, aurora and airglow, ionospheric physics, solar activity, cosmic rays, glaciology, oceanography, rockets and satellites, seismology, gravity measurements, nuclear radiation, and publications. The working groups, composed of scientists from the various delegations, met regularly between the opening plenary session on July 30 and the closing plenary session on August 9.

A review of the flow of data to and among the three IGY World Data Centers indicated that satisfactory progress is being made in this aspect of the IGY if account is taken of the routine problems associated with the collection, checking, handling, mailing, and reproduction of basic data. The Assembly urged, however, that the flow be accelerated and recommended that participants make copies available directly to all three World Data Centers in order to speed up the exchange of data and reduce the reproduction burden on the Data Centers. The Assembly requested that, in addition to the raw data, the World Data Centers also collect reprints of published results of IGY programs, and, in view of the value to scientists of these comprehensive collections of data, that the Centers continue in operation for as long as possible.

The single area in which completely satisfactory agreement was not achieved related to rocket and satellite data. With regard to scientific data from rocket and satellite experiments, alternate proposals were made. One advocated that preliminary data be supplied on a routine basis to the World Data Centers in advance of final publication, the other that only final published papers be supplied routinely, with preliminary data furnished only on specific request. A second point of difference was whether size, weight, and other information should be provided on all objects in orbit, including carrier rockets and nose cones, or only on instrumented satellites. Finally, a question arose as to whether precise orbital data should be supplied or only approximate direction angles for each observing station. The CSAGI has proposed a special committee to consider these three topics, and it is hoped that a satisfactory resolution may be achieved. This would then provide detailed agreement in the rocket and satellite area equivalent to that in the other IGY disciplines.

The Assembly recommended that a World Magnetic Survey be undertaken during the coming period of minimum solar activity. IGY studies provide data during the peak of the sunspot cycle, when the magnetic field undergoes rapid variations. The World Magnetic Survey, however, would provide data on the slow changes of the magnetic field and provide an up-to-date magnetic map. Such surveys are best conducted in magnetically quiet periods, the next of which takes place some four or five years from now. This recommendation will be considered by the International Council of Scientific Unions (ICSU) and by the various members of ICSU, such as our own National Academy of Sciences.

The question of prolonging the IGY for another year was raised by the USSR-IGY Committee. It was decided that the period of intensified geophysical-research effort of the IGY should terminate as planned. However, it was proposed that the coming year be designated "International Geophysical Cooperation-1959" (IGC-1959) and that observational and data-collection activities continue along the general plan of IGY "as far as practicable and at such level and in such fields as may be determined by each participating committee." The resolution has been endorsed by ICSU and its adhering bodies; this will have the following results:

First, it will provide a means for continued interchange of data among countries, and it is planned that data contributed from geophysical research during 1959 would be deposited in the IGY World Data Centers. Second, it will provide a transition period between the present IGY program and subsequent scientific programs in which clear need for further international cooperation arises. The Antarctic and oceanography programs are examples of the latter. ICSU has established special committees for these programs.

The Special Committee on Antarctic Research has already planned a 1959 program for continued efforts by those countries which have been active in the Antarctic during the IGY. A similar committee has been established for oceanography, although the plans for this committee are longer-range. In addition, ICSU will soon consider the establishment of appropriate committees in several other areas, including (i) rocket and satellite research, (ii) solar patrols and alerts, and, perhaps, (iii) the proposed World Magnetic Survey.

Agreement was reached on the publication of processed IGY data and results. A series of volumes, to be published in the *IGY Annals*, will be prepared under the direction of a specialist in each field (the World Reporter). Although complete publication will take several years, the program will afford many advantages: First, economy in publication will be realized through this cooperative, international plan. Second, wide distribution of the IGY results will be possible through a single medium. Third, the long-range burden on World Data Centers should be appreciably reduced by the availability of these volumes of processed data, reports of activities, and research papers.

During the Assembly, a number of special symposia were held. A total of some 200 scientific papers, distributed among the following disciplines, were presented:

Aurora and airglow; cosmic rays; geomagnetism, in a symposium on geomagnetic and ionospheric disturbances; glaciology; ionospheric physics, in symposia on meteors and on the ionosphere; meteorology, in symposia on numerical forecasting, noctilucent clouds, Antarctic meteorology, and nuclear radiation; oceanography; seismology; rockets and satellites, in symposia on satellite orbits, satellite tracking, atmospheric structure (electrical), atmospheric structure (non-electrical), satellite radio observation, extraterrestrial radiation observations, and miscellaneous; and solar activity.

In addition, at all discipline working-group meetings, reports were presented by participating committees on their programs.

Summer Activities—Drifting Station Alpha

This report is based primarily on material supplied by Norbert Untersteiner, University of Washington, and T. Saunders English, University of Alaska.

The scientific program at Drifting Station Alpha, one of the two US-IGY stations established on the drifting ice of the Arctic Ocean, has continued almost without interruption despite severe logistic problems.

During the latter part of April, a part of the floe on which the station was built broke off and newly-formed pressure ridges advanced into the camp area. All but ten persons, including both scientific and supporting military personnel—just enough to keep the program serviced—were evacuated. On May 2, the Alaskan Air Command, 11th Air Division, which is responsible for station logistics, decided to move the camp to an adjacent floe about one mile away. The personnel who had been evacuated were returned and removal operations begun.

The task of moving was difficult because of the roughness of the ice surface and the need to jack up all structures in order to place runners beneath them. Moreover, it was necessary to dig power cable out of the ice in order to salvage as much of it as possible.

Because power cable had to be salvaged, spliced, and installed before rawinsonde observations could be made at the new site, two such readings were missed. The IGY seismic, gravity, oceanography, and magnetic programs of Station Alpha, however, continued on schedule. By May 24 the entire camp—consisting of 21 buildings—had been moved and a runway constructed at the new location.

On June 10, two leads (long, narrow water passages in the pack ice) formed across the new runway. Construction of a replacement runway was hampered by the beginning of the melt season, but by continuous draining through core holes it was possible to ready a strip for a C-54 aircraft on June 22. Shortly thereafter, a crack also formed in this runway. From then until late September, when the first landing of the winter season was made, the station was supplied by airdrop.

Biology

Though not among the disciplines for special IGY study, biological studies were emphasized in the summer program. T. Saunders English of the University of Alaska has been gathering data for an environmental study of the marine life under the floating ice. In addition to instrumental observations of the ice-water environment, the program includes direct observations underneath the ice in "frogman" gear with self-contained breathing equipment.

The amount of light energy in the sea is almost beyond doubt the limiting factor for the photosynthetic process, which is the basis of life in the sea. In the Arctic Ocean, a large portion of the sunlight is blocked off by the floating ice covering 90–95% of the sea surface. Many hypotheses have been put forth about the extent and variation of solar radiation passing through the ice cover. Direct observation of the transmitted radiation, by an undersea diver carrying suitable instruments, seems an excellent way to obtain the data necessary to evaluate these hypotheses. Three divers are using submarine photometers with filters to estimate the amount of light available to the plant life growing under the ice.

The underwater program also includes direct observation and sampling of the marine life on the underside of the ice. Previous work has shown that there is a considerable population of diatoms (microscopic plants with siliceous shells) attached to the underside of the ice; that many crustaceans appear to graze on the diatoms; and that seal feed on the crustaceans. Standard sampling equipment fails to give an adequate estimate of the populations involved in this food chain and gives no insight into natural conditions. Direct inspection by an observer under the ice permits description of the plants and animals on the undersurface of the ice, determination of their relationships to one another, and effective sampling for estimates of the populations involved.

It is hoped that these observations will clarify the relationship of this food chain to the unexpectedly large animal population found in high-latitude Arctic waters.

The phytoplankton (plant plankton) studies begun in 1957 were continued and expanded. Standing-crop samples and large-volume samples were taken for identification of plankton. (Standing-crop samples give a quantitative measure of the numbers and kinds of plants; large-volume samples provide a non-quantitative, overall picture of the marine population.) Preliminary analyses of the standing-crop samples showed the expected increase in productivity for the sunny summer months. Complete productivity studies, which can be only partially accomplished at Station Alpha, will include analyses of oxygen consumption and production, carbon-14 accumulation, and chlorophyll abundance. The data obtained will be analyzed to determine daily, seasonal, and depth variations in plankton productivity.

Samples of sea water for chemical analysis were taken at regular intervals. Preliminary analyses for chlorinity, oxygen, phosphates, silicates, nitrates, and nitrites were made at the station. Other samples will be returned to the mainland for more detailed analysis. The microstratification of the upper layers of the water was studied. A thermal probe was used to measure temperature, and the samples of water taken from specific levels were analyzed. The chemical studies and stratification studies should provide data describing the physical environment of the plankton and the nutrients available in the seawater.

In addition to the near-surface studies, horizontal plankton tows were made at various depths to collect foraminifera (microscopic, one-celled, hardshelled animals), and bottom trawls were taken. The bottom trawls have collected two kinds of echinoderms—brittle stars and sea cucumbers—as well as a number of rocks.

Sea-Ice Physics

The IGY sea-ice physics and glaciology investigations on Station Alpha (see *Bulletin No. 12*) were accelerated during the summer. Observations of ice accretion and ablation (loss, primarily by melting) were continued at the old site even after the camp was moved. (By September 1 the distance between the new and old sites had increased to two miles.) The 1958 melt season began two weeks earlier than in 1957 and lasted one month longer. Ablation during the 1958 melt season was found to be twice as great as in 1957, but less than accretion during the 1957–1958 winter. Thus, the total thickness of the floe increased during the year.

Ice Petrography: Core holes were drilled through the sea ice at regular intervals along lines crossing relatively undisturbed portions of the floe. The cores obtained are analyzed microscopically and chemically; this provides a three-dimensional picture of the fine structure and the salinity of the ice both along the sampling line and to the bottom of the floe. For selected cores, thin sections of ice from 10-cm intervals were prepared, examined microscopically, and photographed. It was possible to correlate the microscopic structure of the ice with its salt content and also to trace individual layers in the ice for horizontal distances of 10 to 20 m. The layer formed during the past winter, 50 to 70 cm thick, is particularly clear and has been observed in most cores.

Mechanics of Sea Ice: On May 14, Andrew Assur and Guenther Frankenstein, of the US Army Snow, Ice and Permafrost Research Establishment, began an intensive study of the strength of sea ice under natural conditions. They measured the tensile and compressive forces needed to break beams of ice cut from the floe; determined salinity and density; measured the electrical resistivity of sea ice; determined the elasticity of sea ice; measured the deformation of ice under load; and surveyed ice conditions in general.

Underwater Sound

Charles W. Senior of the Navy Hydrographic Office and E. P. Kelley of the Underwater Sound Laboratory arrived on June 21 to begin a study of long-range, underwater sound transmission between Station Alpha and Station Bravo, almost 400 mi to the south. The latter is on Fletcher's Ice Island, a large piece of shelf-ice thought to have broken off the Ellesmere Ice Shelf. Sound transmission tests were conducted at various depths. Measurements of vertical distribution of ocean temperature and salinity, which affect sound transmission, also were made.

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IGY Bibliography

"An Interim Bibliography on the International Geophysical Year" has been published by the National Academy of Sciences.

This is the first of a series of bibliographies on the International Geophysical Year to be prepared by the Library of Congress as a joint project of the Library, the Academy, and the National Science Foundation. It is expected that it will be followed by a second interim volume in the spring of 1959 and later by a final complete bibliography listing all references on the IGY of scientific interest collected by the Library of Congress prior to July 1959.

The 64-page publication lists 704 references on the International Geophysical Year published between January 1951 and August 1958. The basis for selection of each entry has been the scientific value, the extent of coverage, historical interest, uniqueness, and to a lesser extent, availability. Titles in Russian, East European languages, and Japanese have been translated into English. The existence of complete translations and English summaries is noted where available.

The Interim Bibliography is priced at $1.00, postage prepaid. Orders should be addressed to the Publications Office, National Academy of Sciences, Washington 25, D. C.

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A monthly survey by the U. S. National Committee for the International Geophysical Year. Established by and part of the National Academy of Sciences, the Committee is responsible for the U. S. International Geophysical Year program in which several hundred American scientists are participating and many public and private institutions are cooperating.

Program in Biological and Medical Sciences, 1958–1959

The Committee on Polar Research of the National Academy of Sciences and its Panel on Biological and Medical Sciences, in cooperation with the National Science Foundation, has prepared a broad program as part of the continuing US scientific research in Antarctic regions. The program, to be pursued primarily in the post-IGY period, is an outgrowth of the interest in life sciences that developed during the course of IGY studies in the physical sciences in this remote area. Australia, Great Britain, Argentina, and other nations are also supporting continuation of biological programs in the south polar regions. Of the twelve US scientists participating in this program, three will remain and continue their work during the austral winter.

At the US Naval Air Facility, on Ross Island in McMurdo Sound, a permanent laboratory will be installed by 1959 to support field studies in biology, medicine, and other life sciences in the coming summer season. In addition to a wide variety of equipment, biological supplies, and culture media, the laboratory will have a library of standard references, special texts, and the scientific reports of past Antarctic expeditions as well as current materials pertinent to Antarctic research.

Human Medicine

Medical studies of the incidence of respiratory infections, the isolation of the organisms responsible for such infections, and the development of new field techniques for their control are being carried out by a medical team supervised by William J. L. Sladen, Johns Hopkins University, Baltimore, Maryland. These studies are being made at the joint New Zealand-United States Hallett Station, at Wilkes Station, and at NAF, McMurdo. The medical team is using a temporary laboratory on board the USS *Staten Island* until the laboratory at NAF, McMurdo is completed. Robert M. Chanock, Respiratory Unit, National Institutes of Health, Bethesda, Maryland, will cooperate in phases of the work to be conducted in the United States. Rainer Goldsmith is conducting the laboratory investigations on board the *Staten Island*.

Ornithology

Ornithological work includes studies of the breeding biology of Antarctic birds, particularly of penguins, the south polar skua, and the giant petrel. The birds are also banded for study of their migration habits. These investigations are partly extensions of the research conducted by Carl Eklund while Station Scientific Leader at the US-IGY Wilkes Station during the 1957–58 period, and of studies initiated by Sladen during his period of Antarctic service with the Falkland Islands Dependencies Survey (UK) on the Palmer Peninsula.

At Wilkes Station, a year-long study of

the social and parental behavior of the Adélie penguin, and of its orientation mechanism in migration, is being undertaken. This research is conducted by Richard Lee Penney, graduate student at the University of Wisconsin, Madison, Wisconsin. Penney is one of the three Americans who will winter over at this station.

Penney is also collecting samples of egg white for C. G. Sibley, Cornell University, who is making a taxonomic study of avian proteins under a National Science Foundation grant.

Animal Parasitology

Parasitological studies of birds and mammals will be made, principally at the IGY Hallett and Wilkes Stations and at NAF, McMurdo. In addition to collections of internal parasites of seals and birds, Sladen and Goldsmith are making a special collection of birds' heads and necks. These will be returned to the United States for study by Gordon M. Clark, biologist and authority on mites inhabiting the respiratory passages of birds. He will study the specimens at the Patuxent (Md.) Research Refuge of the US Fish and Wildlife Service.

Entomology

In the field of entomology, an investigation of land invertebrates is being carried out by Madison E. Pryor, graduate student at the University of Tennessee, Knoxville, Tennessee. He will work at the biological laboratory at NAF, McMurdo. Pryor is one of two biologists who will winter over at McMurdo.

Botany

A special study of Antarctic mosses is being made during the austral summer by Elmer G. Worthley, Sr., Arctic Institute of North America, in the region of Ross Island, McMurdo Sound.

Marine Biology

Marine biology studies are being conducted by six investigators working partly from ships and partly from the laboratory at NAF, McMurdo. A study of the food cycle of marine fauna is being made at Hallett Station and at NAF, McMurdo. It will be continued, by invitation from the New Zealand Oceanographic Institute, aboard the New Zealand oceanographic research vessel HMNZS *Endeavour* during a cruise along the Antarctic convergence zone and in the Ross Sea. (The convergence zone is the region in which the cold waters of the Antarctic current sink beneath and mix with warmer waters of the West Wind Drift.) This work will be carried out by Richard G. Miller, of Long Beach State College, Long Beach, California. He will be assisted by John Resek, Jr., Costa Mesa, California.

Donald E. Wohlschlag, Chairman, Department of Biological Sciences, Stanford University, is studying the ecology of inshore marine invertebrates at NAF, McMurdo. John H. Dearborn, graduate student at Stanford, is assisting him. Dearborn will continue these studies at the biological laboratory at McMurdo during the winter.

Hugh H. DeWitt and James C. Tyler, also graduate students at Stanford University, are accompanying, respectively, the USS *Glacier* through the Ross Sea to McMurdo Sound, and the USS *Edisto* to IGY Ellsworth Station on the Weddell Sea. Under the direction of Wohlschlag, they are carrying out studies on the systematics, or classification, of Antarctic fishes and making other marine biological observations. Particular study is being made of the physiological properties of blood and of anatomical adaptations to feeding habits and habitat.

Tyler is also collecting sera from Antarctic fishes for the Serological Museum at Rutgers University.

Psychology and Psychiatry

An analysis of selection and performance data of wintering-over personnel, based on diary materials, psychiatric evaluations, and interviews, will be conducted by William M. Smith, graduate student at George Washington University, Washington, D. C. The purpose is to evaluate factors that may be useful in selecting scientific personnel for future work in isolated regions; to report on the performances of scientific personnel during their stay in the Antarctic; and to describe the group structure at the scientific stations and the roles played by the individual members of the various scientific parties.

IGY News From Other Countries

A. Progress of the United Kingdom Program

The following account is based on summary reports of the first twelve months of the United Kingdom IGY Program. The reports were presented by the British National Committee for the IGY to the Fifth General Assembly of the IGY, held in Moscow, July 30–August 9, 1958.

The United Kingdom Program, which includes all IGY disciplines, got under way promptly with the start of the IGY on July 1, 1957, and has proceeded according to plan. The activities of the first twelve months produced many significant results. Among them are the discovery of a southward-flowing countercurrent in the eastern Atlantic similar to the one found earlier beneath the Gulf Stream; correlations between auroral activity in the northern and southern hemispheres, and, in the Antarctic, between the aurora and geomagnetic and ionospheric activity; and observations of two distinct radio-wave-reflecting structures in the F layer of the Antarctic ionosphere.

In the Antarctic, the most extensive United Kingdom program is concentrated at the Royal Society IGY Station, at Halley Bay on the eastern side of the Weddell Sea. Here, the entire scientific program, comprising investigations in meteorology, geomagnetism, aurora, ionospheric physics, glaciology, and seismology, was functioning by June 20, 1957.

(Other United Kingdom Antarctic stations are maintained on the Palmer Peninsula and in the South Shetland and South Orkney Islands, near the northern end of the Peninsula. Shackleton Station, on the Filchner Ice Shelf, and South Ice Station, on the polar plateau between Shackleton and the South Pole, although established primarily as bases for the Commonwealth Trans-Antarctic Expedition, also supported programs of scientific investigation—in meteorology and glaciology, in particular.)

Meteorology

In addition to the standard meteorological program, British Ocean Weather Ships in the Atlantic are recording solar radiation. Ozone sounding equipment of the electrolytic-absorption type has been flown on balloons released at Halley Bay, at Malta, and in England, providing data on the vertical distribution of ozone to altitudes of about 20 km. A rapid rise in total atmospheric ozone was observed at Halley Bay in late October 1957; a similar increase occurred just one year earlier.

In the meteorology program at the Royal Society Station, standard surface measurements, including temperature, pressure, humidity, and wind speed and direction, are made continuously or at frequent, fixed intervals. The lowest temperature recorded since establishment of the station was −51°C (−60°F), in July 1957; the highest was 2°C (36°F), in January 1957. A wind speed of 77 knots, almost 90 mph, was recorded in June 1957.

Standard surface observations were made on the Commonwealth Trans-Antarctic Expedition and at Shackleton and South Ice Stations during most of 1957.

Glaciology

The glaciology program includes studies in the Antarctic and in glacier regions of tropical East Africa. An expedition by Sheffield University scientists to Mt. Kilimanjaro was completed in January 1958, and other expeditions to East African glaciers were included in the 1958 program. Field work has been completed on South Georgia Island in the South Atlantic, and glacier-regime studies and other observations have been made in the Falkland Islands. Glacier fluctuations relative to climate during the past 50 years were included in the South Georgia studies.

Royal Society Station: Glaciological investigations during the first twelve months at the Royal Society Station, which lies on a partly grounded ice shelf several hundred feet in thickness, were limited to studies of accumulation and ablation in the vicinity of the station, of temperature gradient within the ice, and of past variations in the net accumulation. Studies of related meteorological factors were made simultaneously. These included radiation balance, heat transfer and variation of temperature in the near-surface layers, and snowfall.

Snow accumulation was measured by use of stakes and in a small pit. Meteorological data served as a guide to the dating of wind crusts and snow deposits. These accumulation measurements were correlated with others made on sledge trips to points as far as 30 mi from the station. Annual accumulation back to 1943 averages 38 cm, with a large total range of 18 to 77 cm.

The report adds that "the detailed notes on the layers appear to provide useful evidence of the meteorological characteristics of each year, for example of the frequency of 'warm periods' in the winter. In several of the summers there is no indication that melting occurred."

Study of the general characteristics of the ice shelf and of the sources which feed it was made by air reconnaissance. The positions of ice-fall areas and crevasses gave some indication of the location and configuration of the coastline proper. The rate of movement of the shelf ice appears to be very slight, but definite.

Commonwealth Trans-Antarctic Expedition: Seismic soundings to determine the thickness of the ice sheet and the nature of the underlying materials were made at 30–70 mi intervals from South Ice Station to the Skelton Glacier. Ramsonde measurements were made frequently and the cores examined. At seismic stations, temperatures were measured at one-meter intervals, to a depth of 11 meters, in the ramsonde holes.

At South Ice, snow accumulation was measured and a study of the effects of the surface micro-climate on accumulation and ablation was made. A 50-ft-deep snow pit was dug for studies of ice-crystal orientation and snow strata. A 3-in bore hole drilled from the bottom of the pit extended these observations to a depth of 100 ft.

Oceanography

United Kingdom research vessels cooperated with vessels of the Woods Hole Oceanographic Institution in the discovery and investigation of a southwest-flowing countercurrent beneath the Gulf Stream (see *Bulletin Nos. 2* and *8*). Detailed measurements were also made, in collaboration with Woods Hole, of the temperature, salinity, oxygen, and other variables across the Atlantic at 24°, 32°, and 48°N latitude.

Cooperative investigations with Norwegian and French research vessels have revealed another countercurrent about 640 km (400 mi) west of Oporto and Lisbon, Portugal. It flows southeastward at speeds of 1.5 to 3 km (1 to 2 mi) per day below a depth of 1400 m (about 4600 ft). Other deep-water studies have been made in the Atlantic west of the English Channel; in the Straits of Gibraltar, Bab-el-Mandeb (between the Red Sea and the Gulf of Aden), and Hormuz (between the Persian Gulf and the Gulf of Oman); and by British weather ships.

In the Antarctic, gravimeter records for Shackleton Station show the rise and fall of the 1300-ft-thick Filchner Ice Shelf with the tide. The report states that "No other method of tidal observation at the head of the Weddell Sea was practical owing to the great depth of the sea (500 fathoms) at the edge of the ice shelf."

Geomagnetism

In the Antarctic, an effort is being made to measure the water currents and associated electrical currents in the Weddell Sea below the edge of the Filchner Ice Shelf. Thus far, the records have failed to show any geomagnetic effects related to such electrical currents.

Aurora

Significant results have been obtained in the aurora program at the Royal Society Station, where auroras were observed on all dark, clear nights. The report states that considerable auroral activity occurred north of the zenith, and there were many full coronas with centers usually 118° above the southern horizon. At times, auroras were seen within 10° of the northern horizon; this corresponds to overhead displays at a position roughly 29° from the geomagnetic pole, if it is assumed that the aurora is 100 km above the earth's surface.

"... the impression gained was that for flaming diffuse surfaces without any rayed structure the motion of the waves of luminosity was directed along the local geomagnetic meridian [rather than toward the magnetic zenith].... When rays were present the waves appeared to move towards the magnetic zenith but this is the effect to be expected when waves of excitation cut across the rays at an angle. It is concluded that in all cases the direction of motion was along the geomagnetic meridian but that the presence of a rayed structure produced a disturbance."

Comparison of auroral data with radio-echo data: The Royal Society Station is equipped with radio-echo apparatus similar to that at the Jodrell Bank Experimental Station at the University of Manchester, England. Although echoes occur much more frequently at the Antarctic station, their general features appear to be the same at both stations.

No correlation was found between specific auroral forms and the sharpness of the radio echoes. Moreover, the fact that echoes are not always received when quiet arcs are present suggests that ionization of sufficient density to cause reflection is associated only with the more active auroral forms.

Comparison of the Halley Bay radio-echo data with similar data for the same period at Jodrell Bank suggests the conclusion "... that the great aurora of the northern hemisphere are accompanied simultaneously by a greatly enhanced activity of the aurora australis."

Comparison of auroral data with magnetic data: Since the Royal Society Station is some distance from the auroral zone, auroras are usually highly active by the time they have moved overhead. This hinders direct correlation with simultaneous magnetic disturbances. Nevertheless, the report states, "There are ... indications that the vertical magnetic disturbance force does not change sign when arcs and draperies pass through the zenith, as should happen if the magnetic disturbance is due to an east-west current flowing along the base of the arc. On the contrary, large vertical disturbances were sometimes observed when a drapery passed overhead. More detailed analysis will be necessary before any definite conclusions may be drawn on this point."

Ionospheric Physics

The program is in general being carried out as planned and the flow of data to the World Data Center C subcenter for Ionospheric Data, at Slough, England, is rapidly increasing. A large volume of all types of ionospheric data has been received from the Royal Society Station in the Antarctic.

Ionospheric measurements at Halley Bay indicate that the station is situated outside the auroral zone. The main features of the daily F-layer variation (layer which reflects high-frequency radio waves) over Halley Bay were:

"(a) . . . very large diurnal variation in the electron density with a maximum near noon in winter despite the absence of significant photo-ionization from the sun.

"(b) . . . suddenness of the change from typical winter to typical summer variations which occurs near the equinoxes.

"(c) . . . small diurnal variation in the electron density in summer which shows a maximum near midnight and a minimum near noon.

"These features are consistent with the hypothesis that the diurnal variations of the F2 layer at Halley Bay are mainly determined by movements of ionization and not by the primary photo-ionization processes."

The report further states that winter-month ionograms show two distinct reflecting structures in the F region ". . . at times between about 1900 LMT [Local Mean Time] and 0200 LMT. One of these is continuous with the dense layer present on the previous noon and the other, . . . first seen at oblique incidence, gradually replaces the former and eventually develops into the dense F layer of the subsequent noon period. The new structure is sometimes first seen at appreciably lower heights than the old F layer and it then gives rise to striking discontinuities in the diurnal variations of the density and height of the layer. . . . The earth's magnetic field at Halley Bay shows unusual fluctuations while this movement is taking place. . . . The new layer is generally dominant before the . . . main period of corpuscular activity, . . . between 0200 and 0900 LMT, and . . . the noon F2 critical frequencies in midsummer and midwinter are practically equal."

In the vicinity of the Royal Society Station, there appears to be very good correlation between auroral and ionospheric activity. Preliminary reports indicate that auroras occurring at the zenith are accompanied by severe radio blackouts.

Daily radio-wave absorption measurements indicate the presence of a sporadic, corpuscle-controlled absorbing layer in the ionosphere along with the normal, solar-photon-controlled absorbing layer. This sporadic layer is densest and occurs most frequently near 0400 LMT, the time of maximum occurrence of total blackouts. Moreover, the daily variation of the sporadic layer is similar to that of the blackouts.

Considerable activity is also shown at 0400 LMT by the radio-echo index, but its daily variation is, in general, shifted to earlier hours. This was unexpected, as similar measurements in the northern hemisphere show a shift to later hours.

Solar Activity

A heliograph for analysis of the Hydrogen-alpha radiation of the sun commenced operation at the Cape of Good Hope in March 1958. This instrument is providing full information for about 30 solar flares each month. The films produced by the heliograph are being analyzed photometrically, and light curves have been prepared for a number of solar flares.

Rockets and Satellites

As the program progressed there was a substantial expansion of effort in the field of rockets and satellites.

Satellites: Working groups on optical (visual and photographic) and radio (including radar) tracking were set up and arrangements made for observation of earth satellites passing over the United Kingdom. Similar arrangements were made at the University College of Ibadan, Nigeria, and at the Radio Research Substation, Singapore.

The photographic and visual observations are being made both at observatories and by amateur astronomers. Radio observations, including doppler studies, and signal-strength measurements have been made at nine or more stations; interferometers and direction-finding equipment are also in use at these stations. Radar observations have been made at Jodrell Bank. Telemetry equipment for recording data from United States earth satellites, loaned by the US-IGY Committee, is operated at Ibadan and Singapore; telemetry signals from USSR satellites have been recorded by the BBC receiving station at Tatsfield, England, and by amateur radio observers.

United Kingdom agencies are issuing orbital predictions for earth satellites.

Rockets: A high-altitude rocket, the "Skylark," has been developed for upper-atmosphere research. Following the first IGY launching at Woomera, Australia, on April 17, 1958, several successful additional launchings have been made. Although the results are still being analysed, "... one interesting phenomenon, believed to be due to the presence of atomic oxygen, is the development of an intense luminescent cloud lasting 3 to 4 minutes from the explosion of the highest sound-ranging grenade at about 120 km [75 mi], ... it is hoped in further experiments to study wind distribution by this means."

Seismology

In Britain, a number of stations are compiling and transmitting seismic data, including observations of microseisms. Eight stations in the West Indies, the Royal Society Station in Antarctica, and a station at Port Stanley, Falkland Islands, are also contributing data.

Small earthquake shocks are recorded frequently at the Royal Society Station. These appear to be local, possibly associated with mountains within a few degrees of the station. According to the United Kingdom report, "No other seismic activity has been traced to the Antarctic continent."

Gravity

A gravity traverse was carried out during the Commonwealth Trans-Antarctic Expedition from Shackleton Station (UK), on the Weddell Sea, via the South Pole to Scott Station (NZ), on McMurdo Sound. Measurements of relative gravity were made with a Worden gravimeter after each camping period and at intervals of about 15 mi along the 2150-mi traverse route. Similar measurements were made at the Royal Society Station.

With US cooperation, the Cambridge University Department of Geodesy and Geophysics made a series of pendulum gravity measurements early in 1958 at eight stations between Teddington, England, and Johannesburg, South Africa. Another such series was planned for 1958 between Washington, D. C., and South America.

Earth tides are being recorded continuously at Winsford, Cheshire, England. The records are sent to Bidston Observatory for reduction and analysis.

B. Antarctic Notes

The following review of plans by 12 nations for scientific activity in Antarctica during 1959 is based on a report in the CSAGI publication, IGY News. *The information for the report was supplied by the Acting Secretary of the Special Committee on Antarctic Research (SCAR) of the International Council of Scientific Unions (ICSU). In general, it appears that research activity in the Antarctic during 1959 will continue at nearly the same level as that maintained during the IGY, which ends on December 31, 1958.*

Argentina: The scientific program at Ellsworth Station will be continued cooperatively by Argentine and US personnel; two US meteorologists will winter-over at Ellsworth Station in 1959 and remain through the 1959–60 Antarctic summer season. The program at General Belgrano Station, on the Filchner Ice Shelf, will continue on a limited basis; other Argentine Antarctic stations will continue at present levels.

Australia: The Macquarie Island, Mawson, and Davis Stations will be maintained. In addition, the program at Wilkes Station will be continued cooperatively by Australian and US personnel; two US meteorologists and one US biologist will be at the station through the 1959 winter and the 1959–60 summer seasons. Oversnow traverses will be conducted from Mawson during the 1958–59 summer season; they will then be transferred to Wilkes Station.

Belgium: The Roi Baudouin Station will remain in operation during 1959.

Chile: All present stations will be maintained in 1959, and the Risopatron Station, destroyed by fire in March 1958, will be rebuilt. Additional studies in geomagnetism, cosmic rays, geology, chemistry, biochemistry, and bioclimatology are planned.

France: The inland Charcot Station will be closed at the termination of IGY, but the D'Urville Station, on the coast, will continue to operate with only slight reductions in parts of the program.

Japan: Reoccupation of Syowa Station by a wintering-over party of 12–15 men is planned for February 1959. (The station was evacuated in the summer of 1957–58 because ice conditions made resupply impossible.) The party will resume the original program of observations in aurora and airglow, cosmic rays, geomagnetism, ionospheric physics, meteorology, glaciology, and seismology.

New Zealand: The program at Scott Station will continue; four US scientists will winter-over during 1959, remaining through the summer of 1959–60. Hallett Station will be operated jointly with the United States on a modified basis. The 1958–59 summer program will include studies in biology, geology, and oceanography; topographic surveying will also be carried out.

Norway: The present scientific program at Norway Station will continue in 1959.

South Africa: There are tentative plans to continue investigations on the Tristan da Cunha Islands, on Marion Island, and, subject to agreement with the United Kingdom, on Gough Island.

United Kingdom: Research in the major scientific disciplines will continue at Royal Society Station; eight other Antarctic stations will continue present programs. Extensive topographic and geologic surveys will continue in the Graham Land region, at the northwestern end of the Palmer Peninsula.

United States: Full operations will continue at the Byrd and South Pole Stations; at the Naval Air Facility, McMurdo Sound; and, in cooperation with New Zealand, at Hallett Station. Oversnow traverse operations will continue; they will be made primarily in Marie Byrd Land, but one is planned for Victoria Land during the 1958–59 summer season. Little America Station will remain in use for some purposes.

Soviet Union: All stations will be maintained except Pioneerskaya, which will be closed in January 1959. The program at Bunger Oasis will be reduced. It was hoped to transfer Sovietskaya Station to the "pole of inaccessibility" during October–November 1958. Additional traverses are planned, including one from Vostok Station to the US-IGY South Pole Station and back to Sovietskaya during the 1959–1960 summer season. It is also planned to establish additional small bases—one south of the Bellingshausen Sea and one in Queen Maud Land—for glaciological and meteorological studies and to assist in future traverses. Oceanographic investigations will continue in the Bellingshausen Sea and in the Antarctic Convergence region, to the north, as well as along the coast of Queen Maud Land.

Auroral Storm of February 10–11, 1958

The following report is based upon material supplied by J. R. Winckler, L. Peterson, R. Hoffman, and R. Arnoldy, School of Physics, University of Minnesota.

During the night of February 10–11, 1958, a very large auroral storm occurred. The storm and other related phenomena were especially well observed and reported, both visually and by a number of instrumental techniques.

Balloon-borne instruments at Minneapolis detected two groups of strong X-ray bursts during the storm. These coincided with two large magnetic bays (increases or decreases in the intensity of magnetic-field components, represented by bay-like indentations on graphs showing variations of magnetic intensity with time); with strong absorption of radio noise; and with the passage across the zenith of a very large amount of auroral luminosity. A cosmic ray decrease also accompanied the storm.

The University of Minnesota workers believe that these terrestrial disturbances were associated with the earth's entry into a large cloud of solar gases that may have originated in a solar flare occurring about a day earlier.

The Aurora

The aurora observed in North America during this storm was one of the most spectacular in recent years. It was reported as far south as Cuba. At Minneapolis, the aurora was seen by visual observers simultaneously with the sudden commencement of the magnetic disturbance, at 0126 UT February 11. The all-sky camera record from Hanover, N. H., shows its appearance a few minutes after the magnetic disturbance began. At Minneapolis, from 0130 to 0330 UT a very intense diffuse green arc covered the sky from 20° above the northern horizon to the zenith and from the eastern to the western horizon. The outstanding feature, however, was the red color, also very intense, which appeared in diffuse patches at high angles above the northern horizon and, at 0200 UT, covered the northern sky from 15–30° elevation as a diffuse arc.

The IGY Auroral Data Center at Cornell University has supplied the following table showing the southern limit of arc forms at one-hour intervals:

UT Feb. 11	00	01	02	03	04	05	06	07	08	09	10	11	12	13
Geomagnetic N Lat.	58	54	50	49	51	48	47	52	50	50	46	48	53	54

It is estimated that the aurora extended from a height of about 200 km to 800 km, and for a distance of about 9600 km east-west and 400 km north-south. In addition to the very high intensity of both the red and green spectral lines, other unusual features of the aurora were the diffuseness and extent of the luminescence, and its persistence for long periods without major changes in form.

Auroral forms or high auroral luminosity were also observed visually or recorded by all-sky cameras at Minneapolis, Fargo, N. D., and Yerkes Observatory, Williams Bay, Wisc., twice during the second phase of the storm. On the first occasion, movement was northward. On both occasions—beginning at 0620 and 0848 UT—they were exactly coincident (on the order of one minute) with the appearance of X-ray bursts, magnetic bays, and cosmic-noise absorption.

Related Solar Phenomena

Considerable solar activity was present for several days prior to the terrestrial storm; hence, the solar-terrestrial relationship is not completely certain. However, the outstanding solar event of the period was a flare, reported by Honolulu Observatory as Class 2; it started at 2108 UT February 9 and ended at 2302 UT the same day, with maximum phase at 2140. The flare was also observed by Sacramento Peak Observatory (N. Mex.), which classified it as 2+. Large radio-noise fluxes were reported by several stations during the flare.

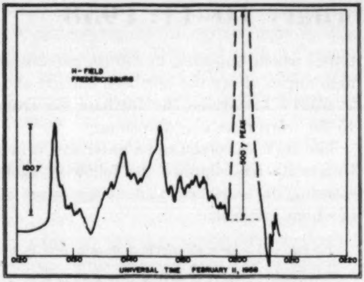

Fig. 1. *Trace of Rapid-Run Magnetogram at Fredericksburg Observatory for First Part of Auroral Storm of February 10–11, 1958. The 500 γ peak was accompanied by large earth-current disturbances.*

Magnetic Storm Phenomena

The terrestrial effects of this storm began at 0.125.7, ± .2, UT on February 11, according to the rapid-run magnetogram of Fredericksburg (Va.) Observatory. (Figure 1 shows the record of this instrument for the first phase of the storm.) The horizontal component (H) of the earth's magnetic field immediately showed a bay of $+117\gamma$ (one gamma, γ, equals 1/100,000 gauss; the earth's total magnetic-field strength is about ½ gauss in middle latitudes). A second sharp, positive bay appeared at 0159.0, ±.1; it followed a disturbed period and was larger than the first, reaching a peak value estimated at about $+500\ \gamma$. This sudden increase in the horizontal component (H) was accompanied by sharp drops of about 150 γ in the vertical component (Z) and 30 γ in the magnetic declination (D). It is assumed that these pulses represent the initial encounter of the solar gas cloud with the earth's dipole field, the sudden appearance of ionospheric current systems, or both. If one assumes a relative speed between the earth and the solar stream of 1400 km/sec, then a time lapse of 0.1 min for an appreciable change in H to occur corresponds to a relative movement of the solar stream of about two earth radii.

If the sudden commencement of the magnetic disturbance is associated with the solar flare that occurred at 2108 UT on February 9, the transit time is approximately 28 hours, indicating a speed of 1400 km/sec. This speed lies within the range of values often postulated for solar corpuscular streams. In addition, the over-all strength of the storm field, with bays of 1000 γ, below the auroral zone, classifies this storm as an extreme one.

Earth Currents: Large earth currents were observed coincident with the horizontal-component peak at 0159. A communication from T. E. Talpey, of the Bell Telephone Laboratory, Murray Hill, New Jersey, states that the earth's potential at the western end of the North Atlantic Telephone Cable dropped from a maximum of about 2650 volts at 0202 UT on February 11, through zero to a peak in the opposite direction at 0209 UT. The current was being driven from west to east through the cable. The section of cable between Clarenville and Sydney Mines, Nova Scotia, at about the same times as the peaks at the western end of the trans-Atlantic section, exhibited peaks of 1450 and, in the opposite direction, 1100 volts. The cable from northern Washington State to Alaska had a maximum of only 250 volts, and the California-Hawaii cable showed no major voltage changes.

The observed earth current peak seems to be an induction effect associated with the second, and largest, of the two magnetic peaks. According to the observations, the recorded current flow was from west to east, H increased, and Z decreased. The total storm field is a north vector increasing initially. The circuit loop of the earth current, if considered to lie in a vertical east-west plane, requires a return path through the sea *above* the cable. However, derivation of the potential in the water gives only about 15 volts around the circuit, compared to the measured maximum of 2650 volts. (The circuit cannot be closed *under* the cable as the polarity would be wrong for an induction effect associated with the horizontal-component bay.)

It is felt, therefore, that the earth current is apparently part of a system flowing in the earth's surface and associated with changes in the vertical component in an unexplained way. The current system seems to be centered over the eastern United States.

Remainder of Storm: The remainder of the magnetic storm was characterized by two large negative bays in the horizontal component (see Fig. 2). The bays were closely associated with the sudden appearance of intense auroral activity passing the zenith in the vicinity of Minneapolis.

Balloon Observations of Auroral X-Rays

Following the discovery of X-rays penetrating to balloon altitudes at Minneapolis during auroral storms on three occasions in 1957 (see *Bulletins 10* and *15*), attempts have been made routinely to prepare launchings when strong storms are forecast. A balloon launched at 0445 UT on February 11 encountered the first detectable X-ray bursts at 0622, coincident with the major decrease in the first large magnetic bay of the second phase of the storm; these bursts continued until 0730. A second large period of bursts occurred at 0850, coincident with the second magnetic bay of this phase (Fig. 2).

It is thought reasonable to assume that both the changes in conductivity of the ionospheric E-layer, which produced the magnetic bays, and the observed X-rays had a common origin in electrons produced by the solar gas stream. These electrons may be accelerated several earth radii from the earth by an interaction between the earth's dipole field and the neutral plasma from the sun. Their energies would lie in the range from 40–100 kv or higher; most of their energy, however, would be lost in the atmosphere as ionization and as the visible auroral light. About 1/1000 of the energy would be radiated as Bremsstrahlung X-rays (see *Bulletin No. 10*) the higher-energy components of which are detected at balloon levels (about 100,000 ft).

Cosmic Noise Absorption

The large absorption of cosmic radio noise at 18 megacycles/sec was observed exactly coincident with the magnetic bays and the X-ray bursts. The absorption was observed, at Boulder, Colorado, both with a vertically beamed antenna and with an interferometer

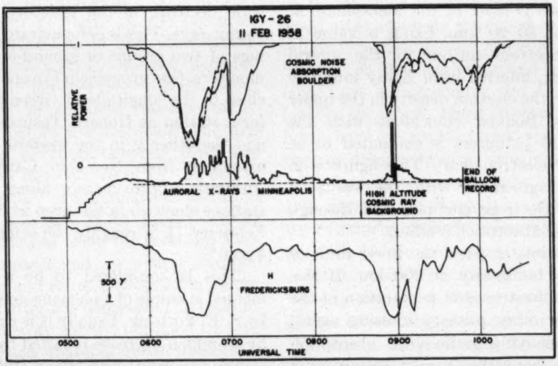

Fig. 2. *Comparison of Measurements of the Horizontal Component of the Magnetic Field at Fredericksburg, Auroral X-Rays at Minneapolis, and Cosmic-Noise Absorption at Boulder. Intense, widespread ionization appears to have occurred twice, at approximately 0630 and 0900 UT.*

directed at an elevation angle of 35° to the northeast. The similarity of the records is good evidence for a very widespread increase in ionospheric electron density extending north-south for at least 150 km. Heavy overcast at Boulder prevented direct observations of the aurora, but the correspondence, even in fine detail, of the fluctuations of the output of the two antennas implies simultaneous fluctuation of the primary phenomena over distances of hundreds of kilometers. Furthermore, the correspondence of data among Fredericksburg, Minneapolis, and Boulder (Fig. 2) shows that the major primary fluctuations were simultaneous over distances of thousands of kilometers.

Correlation of X-Rays, Magnetic Bays, and Cosmic Radio-Noise Absorption

The large changes in the magnetic-field H component, the strong cosmic-noise absorption, the auroral X-rays, and the general presence of the aurora itself, are all consistent with a very intensified bombardment of the ionosphere by high-energy electrons between 0530–0700 UT and 0830–0930 UT on February 11 over central United States.

It is assumed that cosmic-noise absorption during an auroral storm occurs mainly in the upper D-layer of the ionosphere, at altitudes of 80–90 km. Using a value of 6×10^6 electrons/cm^2/sec for the auroral electron flux, inferred from X-ray intensity and energy, the electron density in the upper D-layer at Boulder coincident with the February 10–11 aurora is computed to be 1.2×10^5 electrons/cm^3. This figure is in reasonable agreement with the value of 1.4×10^5 electrons/cm^3 obtained through cosmic-noise-absorption studies.

Visual estimates place the lower limit of the auroral luminosity at 200 km. If this marks the lowest level of penetration of the electrons or other primary ionizing agent, the accompanying radio-noise absorption must arise from the X-rays acting as a secondary ionizing agent—penetrating to much lower levels, ionizing the E and D layers, and appearing at balloon heights. Only 10^{-3} to 10^{-4} of the electron energy appears as Bremsstrahlung X-rays and only high-energy X-rays reach balloon levels; hence, the X-ray energy falls far short of the amount needed to account for the D-layer electrons causing the cosmic-noise absorption. Therefore, either the estimated height of 200 km was too high and the lower border of the aurora was actually at the usual height of 75–100 km, or electrons or other particles carried considerable energy downward, below the visual auroral border. Possibly, the visual luminescence is associated with protons at higher levels, while electrons constituting an equal or nearly equal current penetrate to lower levels producing the ionospheric effects without large amounts of visual luminosity.

The large magnetic bays observed at Fredericksburg coincident with the X-ray bursts may be attributed to an increased conductivity of the ionospheric E-layer, owing, probably, to the same ionizing agent that produced the cosmic-noise absorption phenomena.

Cosmic Ray Phenomena

The storm was accompanied by a worldwide decrease in the intensity of galactic cosmic rays. This is demonstrated by recordings of two groups of ground-level neutron monitors. One group is in Europe and Africa, close to the longitude of Greenwich, except for a station at Hobart, Tasmania (145°E), and the other is in the western hemisphere extending from Northern Canada to the Antarctic approximately along 90°W. All stations show an initial drop at 0200 UT on February 11 of roughly the same amount—4 to 6%.

(This is considered to be a well-documented example of a phenomenon discovered by S. E. Forbush. Usually it is characterized by a sudden decrease followed by a slow recovery requiring several days, and frequently much longer periods. Although the decrease applies to all energies of primary cosmic rays,

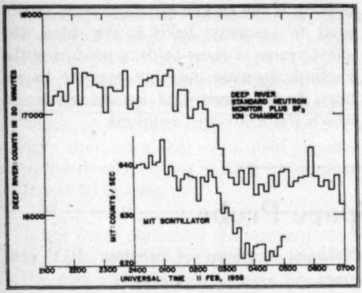

Fig. 3. *Cosmic-Ray Counting-Rate Records for Neutron Monitor and Ion Chamber at Deep River, Canada, and for Scintillation Counter at the Massachusetts Institute of Technology. The "precursor" appears at 0127 UT; the major decrease begins at approximately 0200. Canadian information by courtesy of Hugh Carmichael; scintillator information from Palmeira and Williams,* Il Nuovo Cimento, *Vol. III, 1958, p. 352.*

the low-energy part of the spectrum is affected to a larger extent than the high.)

Another feature of the Forbush-type decrease, which seems to have been reported for the first time in this event, is a "precursor" drop in intensity that occurred closely coincident with the sudden commencement of the magnetic storm, at 0127 UT. As shown in Figure 3, the precursor drop is about 0.5% in the scintillation-detector record and 1% in the neutron-monitor and ion-chamber record. Both records show an apparent increase in intensity just before the precursor. The major decrease occurred between 0200 and 0330 UT and was completed by the end of the "first phase" of the magnetic storm, at the same time that H at Fredericksburg (Figure 1) dropped below the prestorm level.

High altitude soundings with a standard ion chamber and counter were taken before, during, and after the decrease. The total influx of cosmic-ray energy, obtained by integrating the ion chamber rates throughout the atmosphere, dropped 14.9% during the storm; by February 16 it had recovered to within 8.4% of the February 8 value.

Discussion

All the phenomena described are consistent with the passage of the earth into a remarkably intense solar cloud. This cloud may have originated in the solar flare beginning at 2108 UT February 9 and ending at 2302 UT February 9. According to the magnetic records, the terrestrial disturbances began at 0127 UT February 11, and by 24 hours later had fallen to a low level. It may be assumed that the earth was clear of the cloud by that time.

If the cloud originated within the two-hour interval of the flare and required 24 hours to pass the earth, considerable velocity dispersion must have been present in the solar gas. The velocity range of particles in the cloud must have been about 700 to 1400 km/sec, and the radius of the cloud when passing the earth about 0.5 astronomical units (the distance from earth to sun). The minimum lateral extent, estimated from the angular position of the flare with respect to the sun-earth line, was about 0.25 astronomical units near the earth.

The velocity dispersion requires that the slower solar particles predominate later in the storm. The leading edge of the cloud must have been exceedingly well defined and on the order of an earth radius across. The cloud must also have contained considerable internal structure, as revealed by the "spikes" in the first phase and by the two large bays accompanying the X-ray bursts later in the storm. These structural features must have persisted during the sun-earth passage despite the large velocity dispersion.

The process of tracking these features back to a specific series of events in the flare would be extremely difficult. Nevertheless, it is possible to conclude that either the flare emitted considerable matter in very discrete velocity groups, or that a non-linear propagation effect intensified certain portions of the stream, in particular the leading edge and several internal regions.

This storm is unique with respect to the great intensity of the associated ionospheric phenomena; this may reasonably be attributed to an exceptionally high density of the solar gas enveloping the earth. In contrast, the modulation of galactic cosmic rays, while appreciable, is in no way exceptional when compared with other Forbush-type decreases. If the cosmic-ray decrease is attributed to magnetic fields in the cloud, the effectiveness of these fields in producing the Forbush decrease does not seem to be related to the amount of ionized matter in which the fields are contained.

First Deep Space Probe

The first probe into deep space was launched from Cape Canaveral, Florida, at 3:42 pm EST on October 11, 1958. Though it did not reach its maximum objective, the environs of the moon, the space probe, named Pioneer, reached a record altitude of approximately 72,800 mi (63,200 nautical mi) and telemetered much scientific information to earth.

The probe was launched by the Air Force Ballistic Missile Division, under the direction of the National Aeronautics and Space Administration, as a contribution to the National Academy of Sciences' IGY program.

Launching: The launching vehicle was a four-stage rocket with a total length of 88.1 ft and weighing approximately 112,000 lbs. The first stage, or booster, was a standard Thor, about 61 ft long, 8 ft in diameter, and weighing approximately 106,600 lbs. It develops about 150,000 lbs of thrust. The second stage was a modified Vanguard second stage, a liquid-fueled rocket 18 ft long, 32 inches in diameter, weighing 4612 lbs. I

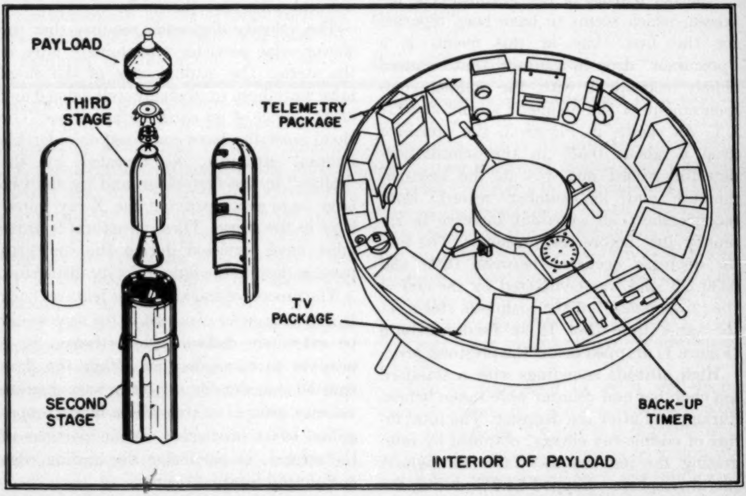

Fig. 4. *Upper Stages and Payload of Pioneer Space Probe. Prepared by Space Technology Laboratories.*

develops a thrust of 7700 lbs. The third stage was an advanced version of the Vanguard third stage, a solid-propellant rocket five ft long, 24 inches in diameter, weighing 597 lbs, and developing about 3000 lbs of thrust. A fourth or terminal stage, to be fired 2.61 days after launching, was a solid-propellant rocket developing up to 2200 lbs of thrust. It was 30 in long.

Eight small vernier rockets were attached to the lower portion of the terminal vehicle to impart velocity and vector corrections to the payload immediately after burnout of the third stage. Spin stabilization of the payload was accomplished by means of spin rockets.

A velocity of 35,250 ft/sec had been planned for the probe. However, because Pioneer traveled about 3.5° above the designed flight path, the actual velocity attained was about 34,400 ft/sec.

Payload characteristics: The toroidal-shaped payload, pierced by the terminal-stage rocket, was 29 inches in diameter and weighed 85 lbs (see Fig. 4). The weight of the instrument package itself was approximately 39 lbs. Pioneer was constructed of Fiberglas, and was painted in a special pattern as a means of controlling temperatures.

Instrumentation: Pioneer carried instrumentation to measure radiation encountered in space; the magnetic field of the earth and of the moon; density of meteoric matter in the payload's flight path; temperatures within the scientific package; and to obtain a crude electronic picture of the surface of the moon—the so-called TV scanner.

The ion chamber used to measure radiation was built to a design developed by James A. Van Allen and Carl E. McIlwain at the State University of Iowa. The Air Force Cambridge Research Center designed the micrometeorite equipment, which was built by the Space Technology Laboratories. STL, designer and producer of Pioneer, had responsibility for over-all scientific direction of the probe. STL also developed the magnetometer and temperature experiments. The scanning system was developed by the Naval Ordnance Test Station, China Lake, California.

Preliminary inspection of the scientific data by Van Allen and his associates at State University of Iowa indicates that the probe may have traversed the Van Allen radiation belt as it penetrated into space; temperatures within Pioneer remained within the range of human survival, if not comfort. More detailed reports of these and other experiments will be made available to the scientists of the world as soon as possible.

Tracking: Five prime stations tracked the Pioneer. They are located at Manchester, England (the Jodrell Bank radio telescope of the University of Manchester); Singapore, Malaya; Hawaii, T. H.; Cape Canaveral, Florida; and Millstone, Mass. All but the Singapore station were equipped to obtain positional data on Pioneer, and all stations recorded telemetry data. These stations, and the NASA Minitrack stations (via the NRL operations center at Cape Canaveral), funneled their information to the Data Reduction Center of STL at Inglewood, California.

The Hawaii prime tracking station was last to have contact with Pioneer, at 10:46 pm EST, October 12, 1958, as it fell back toward the earth. The probe presumably disintegrated in the earth's atmosphere over the South Pacific shortly thereafter.

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